Volume 55 March-April 1960 Number 2

Economic Geology

and the

Bulletin of the Society of Economic Geologists

CONTENTS

A Comparative Study of Major Ore Deposits of Central Bolivia. Part I....*F. S. Turneaure* 217
Genesis of the Gore Mountain Garnet Deposit, New York....*P. Bartholomé* 255
Manganese Oxides and Associated Minerals of the Nsuta Manganese Deposits, Ghana, West Africa....*R. K. Sorem and E. N. Cameron* 278
Composition and Age of the Temiscamie Iron-Formation, Mistassini Territory, Quebec, Canada....*T. T. Quirke, Jr., S. S. Goldich, and H. W. Krueger* 311
The Genesis of Chrysotile Asbestos in the Cassiar Asbestos Deposit, Northern British Columbia....*Hubert Gabrielse* 327
The Discovery of A Copper-Zinc Deposit at Garon Lake, Quebec....*G. F. Joklik* 338
Some Cation Substitutions During the Formation of Phosphorite from Calcite....*L. L. Ames, Jr.* 354
Primary Mineralization of Uranium-Bearing "Siliceous Reef" Veins in the Boulder Batholith, Montana: Part II—The Veins....*B. H. Bieler and H. D. Wright* 363
Rejuvenation of Pitchblende in Hercynian Ore Deposits....*C. F. Davidson* 383
Chalcopyrite Blebs in Sphalerite at Johnson Camp, Arizona....*Arthur Baker III* 387

Scientific Communications:

Commercial Chrysotile Deposits, Baie Verte, Notre Dame Bay District, Newfoundland—Preliminary Notes....*W. James Bichan* 399
Supplement to Vademecum of the Russian Geological Periodicals..*Eugene A. Alexandrov* 401

Discussions:

The White Pine Copper Deposit....*Walter S. White* 402
Huronian Uraniferous Conglomerates....*Stuart M. Roscoe* 410

Reviews:

New Zealand Coals, Their Geological Setting and Its Influence on Their Properties (R. P. Suggate)....*Gilbert Cady* 415
Dana's Manual of Mineralogy, 17th Edit.... 416
Petroleum Geology, 2nd Edit. (K. K. Landes).... 417
Structural Methods for the Exploration Geologist (P. C. Bagley).... 417
Rock to Riches (C. H. Dunning and E. H. Peplow, Jr.).... 418
Books Received....*John E. Cotton and Cyrus W. Field* 418

Scientific Notes and News.... 426

PUBLISHED SEMI-QUARTERLY

Six Dollars Fifty Cents a Year, One Dollar Twenty-five Cents a Copy

THE ECONOMIC GEOLOGY PUBLISHING COMPANY

Printed by Lancaster Press, Inc., Prince and Lemon Streets, Lancaster, Pa.

Second-class postage paid at Lancaster, Pa.

Economic Geology

and the

Bulletin of the Society of Economic Geologists

Issued Semi-Quarterly (Jan.-Feb., Mar.-Apr., May, June-July, Aug., Sept.-Oct., Nov. and Dec.) and sent to subscribers on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15.

Manuscripts for publication should be sent to the Editor, **ALAN M. BATEMAN, at Yale University, Yale Station, New Haven, Conn.** It is requested that contributors exercise care in writing *scientific* and *proper names*. References to other publications should be in accordance with the forms used in the pages of this journal. The manuscript should be typewritten with double space lines and must be preceded by *a brief abstract*. Galley proof will be sent authors only where a request to this effect accompanies the manuscript, or when, in the editor's opinion, the subject matter is such as will require correction by the author.

Reviews should conform to the journal usage. Review Committee: The Editor, C. H. Behre, L. C. Graton, J. T. Singewald, Jr., J. Gilluly, A. F. Buddington, W. H. Newhouse.

Books and Pamphlets for review should be sent to the Editor.

Reprints. Contributors desiring reprints of their papers may obtain them by filling out the order slip which will be attached to the galley proof when it is sent to the author. Provided the order slip is received by the editor, *with the return of the proof*, 50 reprints without covers will be furnished without charge. Reprints of discussions and informal communications are not furnished free of charge except when they exceed four pages in length when 50 will be supplied without charge. Reprints of reviews are not supplied. Additional reprints will be furnished at approximately the rates given in the table below (effective with No. 5) when ordered *in advance of publication*. The rates apply only to plain text, with line engravings. Papers containing folded maps or plates will be more expensive.

The following rates do not include free carriage. *Postage or express must be paid by the author.*

	4 pp. 1–4	8 pp. 5–8	12 pp. 9–12	16 pp. 13–16	20 pp. 17–20	24 pp. 21–24	28 pp. 25–28	32 pp. 29–32	Covers
50 copies.....	$4.20	$6.65	$10.40	$10.85	$14.15	$16.25	$18.70	$19.95	$5.75
100 "	5.00	7.95	12.00	13.30	17.00	19.95	23.30	25.00	7.80
Additional copies per C.	1.70	2.55	4.20	5.00	5.85	7.50	9.15	10.00	3.75

For 500 copies deduct 5%; for 1000 copies or more deduct 10%. For more than 32 pages add cost per schedule to make total. Example: For 44 pages add cost for 32 pages and 12 pages. The 50 copy price is the minimum charge.

Covers: Standard covers are of the same style of type and paper as the cover of the journal, and bear the title of the article and name of its author. Special printing on cover is charged for at the cost of composition.

Plates are $4.20 for the first 50 if printed on one side, and $3.15 per "C" for additional's; printed on both sides, $6.30 for the first 50, and $4.70 per "C" for additional's.

Collotype plates are 8 cents each for each additional reprint over the 50 copies furnished free. Example: An extra 50 reprints containing one collotype plate would cost $4.00; 2 collotype plates, $8.00.

Note: For any reprints requiring additional composition or changes, either in text or cover, an extra charge will be made.

The retail prices of single reprints when available from the office of the Business Manager are as follows:

1–4 pp. 15c	5–8 pp. 20c	9–12 pp. 25c	13–20 pp. 30c	21–28 pp. 35c
29–36 pp. 40c	37–44 pp. 45c	45–52 pp. 50c	53–60 pp. 55c	61–68 pp. 60c

Subscriptions. The price of the journal to subscribers in the United States and its dependencies is $1.25 for a single copy, or $6.50 a year for eight numbers effective July 1, 1953. To subscribers in Canada, Cuba, Mexico, Spain, and countries in Central and South America, except Dutch and French Guiana, the annual rate is $6.80; to other countries, $7.25.

Forwarding. Subscribers wishing their journal to be forwarded to a new address should leave postage for that purpose with the Postmaster at their old address.

Missing numbers will be replaced without charge if claim is made within four weeks after the date of issue of the following number, provided that the neglect to receive them is not due to neglect to arrange for their forwarding.

Remittances should be made payable to the **ECONOMIC GEOLOGY PUBLISHING COMPANY,** and should be mailed to **M. M. LEIGHTON,** Business Manager, Urbana, Illinois, to whom also all **Business Communications** should be addressed.

Foreign Agents. The Technical Bookshop, Salisbury House, London Wall, London E. C. 2, England, British Agents.

Indexed in the Industrial Arts Series.

LANCASTER PRESS, INC., LANCASTER, PA.

Second-class postage paid at Lancaster, Pa.

ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS

EDITOR: ALAN MARA BATEMAN
Yale University, New Haven, Connecticut

BUSINESS EDITOR: MORRIS M. LEIGHTON
Illinois Geological Survey, Urbana, Illinois

ASSISTANT EDITORS

H. E. MCKINSTRY, *Harvard University*
M. LEROY JENSEN, *Yale University*
JOE W. PEOPLES, *Wesleyan University*
J. D. BATEMAN, Toronto, Ont.
R. H. JAHNS, *California Institute of Technology, Pasadena*

ASSOCIATE EDITORS

D. F. HEWETT
U. S. Geological Survey, Menlo Park, Calif.

A. I. LEVORSEN
Tulsa, Okla.

B. S. BUTLER
University of Arizona, Tucson, Ariz.

W. E. WRATHER
Washington, D. C.

A. N. SAYRE
U. S. Geological Survey, Washington, D. C.

L. C. GRATON
Orange, Connecticut

E. S. MOORE
University of Toronto, Toronto, Can.

GEORGE W. MOREY
U. S. Geological Survey, Washington, D. C.

PER GEIJER
Djursholm, Sweden

P. F. FOURMARIER
Liège University, Liège, Belgium

M. S. KRISHNAN
Andhra University, Waltair, India

T. W. GEVERS
University of the Witwatersrand, Johannesburg, S. Africa

C. F. DAVIDSON
St. Andrews University, Fife, Scotland

J. A. BROGGI
Instituto Geologica, Lima, Peru

TAKEO WATANABE
University of Tokyo, Tokyo, Japan

KONRAD B. KRAUSKOPF
Stanford University, California

PAUL RAMDOHR
University of Heidelberg, Heidelberg, Germany

A SEMI-QUARTERLY JOURNAL PUBLISHED BY
THE ECONOMIC GEOLOGY PUBLISHING COMPANY

2, England, British Agents.
Indexed in the Industrial Arts Series.

LANCASTER PRESS, INC., LANCASTER, PA.

SOCIETY OF ECONOMIC GEOLOGISTS

THE PUBLICATIONS OF WHICH CONSTITUTE
A PART OF THIS JOURNAL

OFFICERS FOR 1960

DUNCAN R. DERRY, *President*
CHARLES F. PARK, *Vice President*

PHILIP J. SHENON, *President-Elect*
JOHN K. GUSTAFSON, *Vice President-Elect*

HAROLD M. BANNERMAN, *Secretary*, U. S. Geological Survey, Washington 25, D. C.

JOSEPH T. SINGEWALD, JR., *Treasurer*, Johns Hopkins University, Baltimore 18, Maryland

Councilors

1960	*1961*	*1962*
PHILIP W. CHASE	VINCENT D. PERRY	S. WARREN HOBBS
ROBERT M. GARRELS	STANLEY DAVIDSON	LYMAN H. HART
EDWARD H. WISSER	DESMOND F. KIDD	VINCENT C. KELLEY

Regional Vice Presidents

A. PAUL GERHARD SOHNGE, Africa.....KINGSLEY CHARLES DUNHAM, Europe
LUIS SANTOS-YÑIGO, Asia.....J. RUBEN VELASCO, North America
HADDON F. KING, Australia.....ALBERTO BENAVIDES Q., South America

Executive Committee

DUNCAN R. DERBY, *Chmn.* — JOSEPH L. GILLSON — HAROLD M. BANNERMAN
CHARLES F. PARK — PHILIP J. SHENON — JOSEPH T. SINGEWALD, JR.

Standing Committees for 1960–61

Finance Committee

JOSEPH T. SINGEWALD, JR., *Chairman* — OLAF N. ROVE — J. K. GUSTAFSON

Program Policy Committee

CHARLES A. ANDERSON, *Chairman* — CHARLES F. PARK, JR. — J. K. GUSTAFSON
J. P. POLLOCK — WESTON BOURRET

Program Committee

M. L. JENSEN, *Chairman* — PAUL AVERITT — F. G. SNYDER
JAMES P. POLLOCK — H. E. HAWKES, JR. — H. M. BANNERMAN, *ex officio*

Committee on Publications

DUNCAN R. DERRY, *Chairman* — CHARLES A. ANDERSON — R. H. JAHNS

Nominating Committee

D. F. KIDD, *Chairman* — JAMES BOYD — CARL TOLMAN

Admissions Committee

J. E. THOMSON, *Chairman* — J. C. FRYE — R. B. FULTON, III
CHARLES F. PARK, JR. — ROBERT M. GARRELS

Auditing Committee

A. N. SAYRE, *Chairman* — THOR KIILSGAARD

ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF
ECONOMIC GEOLOGISTS

VOL. 55 MARCH–APRIL, 1960 NO. 2

A COMPARATIVE STUDY OF MAJOR ORE DEPOSITS OF CENTRAL BOLIVIA. PART I

F. S. TURNEAURE

CONTENTS, PART I

	PAGE
Abstract	217
Introduction	218
Geological setting of the ore deposits	219
Potosi district	220
Llallagua-Oruro region	224
Structural geology	231
Regional structure	231
Vein systems and late faults	235
Description of the vein systems	236
Stress analysis	241
Description of the ore deposits	249
General features	249
Wall-rock alteration	251

ABSTRACT

The present article describes five major ore deposits of the Eastern Andes of central Bolivia, the tin deposits of Llallagua, Huanuni and Morococala, and the tin-silver deposits of Potosi and Oruro. The deposits at Potosi, Llallagua and Oruro are associated with porphyry intrusions of middle(?) Tertiary age, whereas the veins of Huanuni and Morococala occur in altered sedimentary rocks. In the Llallagua-Oruro region, the Paleozoic sedimentary formations of northwesterly trend are cut by numerous transverse faults, many of which seem to be related to the early folding. Two longitudinal faults of the strike-slip type at Llallagua belong to a late period of deformation.

The ore deposits are all of the multiple vein type. The simpler vein patterns correlate with regional stress, but those of greater complexity are probably the result of combined regional and local stress. Narrow veins and stringer lodes account for most of the ore, but some sheeted zones, stockworks and breccia lenses have been productive.

Mineralization was long continued, and hydrothermal alteration largely preceded vein filling. Chlorite, sericite and quartz are characteristic of both the tin and tin-silver deposits; tourmaline occurs with the tin ores. Minerals typical of the tin veins are quartz, cassiterite, bismuthinite, pyrrhotite, stannite, marcasite, pyrite, siderite and minor teallite or franckeite. The tin-silver ores contain cassiterite, pyrite, stannite, sulfosalts of lead and silver, alunite and kaolinite. Many other minerals occur in lesser amounts.

An unusual temperature range is indicated; maximum temperatures of 400° to 500° C were probably reached during the early stages of mineralization, the temperature decreasing to 100° C as mineralization came to a close. Early deposition took place in a neutral to slightly alkaline environment, but the vein mineralogy suggests that the solutions became slightly acid during the late stages of vein growth. Cassiterite is associated with pyrrhotite in the tin ores but with pyrite in the tin-silver ores, a contrast that may be related to the sulfur concentration of the ore fluid.

The ore deposits were formed in the near-surface, volcanic environment, characterized by extreme changes in temperature and pressure. Rapid drop in pressure as well as in temperature may have been a factor in the change from silica deposition to silica leaching during hydrothermal alteration, in the formation of bonanza ore shoots, and in the development of ore fluids of acid reaction. Combining the features of high temperature and shallow depth, the deposits exemplify the xenothermal type. The degree of telescoping is perhaps greater in the tin ores than in the tin-silver ores.

INTRODUCTION

THE metallogenetic province of the Eastern Cordillera of the Bolivian Andes has long been famous for deposits of tin and silver, but the belt also includes significant deposits of other metals, notably tungsten, lead, zinc, and antimony. In the northern part of the province, the ore deposits are closely related to the small batholiths of the Cordillera Real and exhibit a zonal arrangement with respect to the intrusives. In central Bolivia, the deposits are irregularly distributed and lack the unity of those to the north.

In the present review, five outstanding ore deposits of the Eastern Cordillera of central Bolivia have been selected for comparison: the tin-silver deposits of Potosi and Oruro and the tin deposits of Llallagua, Huanuni and Morococala (Fig. 1). The deposits are all of the multiple vein type, yet they show wide variation in geological setting and details of structure.

Acknowledgments.—During a period of twelve years in Bolivia, I had an opportunity to study the five districts under review. I am grateful to the managements of Patiño Mines & Enterprises Consolidated and of Mauricio Hochschild, SAMI, for their support of the field investigations and for permission to present in 1951 a paper on the vein structure and ore-shoot distribution.

Many able geologists have been associated with me in my work in Bolivia, and acknowledgment is made to them at appropriate places. In summarizing the mineralogy of the ores, I have been aided by published descriptions of the ores of Potosi, Llallagua and Oruro, and by unpublished reports covering laboratory studies of the ores of Morococala and Huanuni.

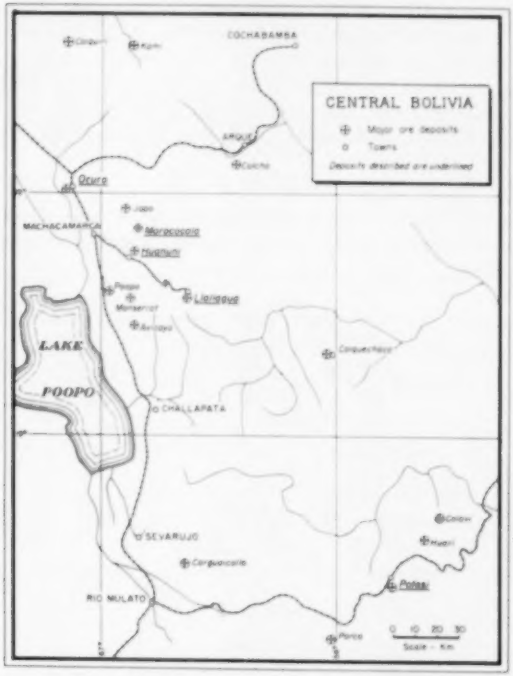


FIG. 1. Sketch map showing major ore deposits of central Bolivia.

An early draft of the manuscript was read by Drs. F. M. Chace, R. M. Garrels, E. N. Goddard, W. C. Kelly and H. E. McKinstry, and I am most grateful for their constructive comments and suggestions. I also wish to thank Dr. Kelly for his assistance in the three dimensional analysis of the vein structure and Dr. K. K. Landes for his helpful advice. Mr. S. B. Keith supplied a valuable suite of specimens from the outer zone at Llallagua, which supplemented my own collection. Financial assistance was obtained from a grant of the Horace H. Rackham School of Graduate Studies, University of Michigan. Mr. D. L. Bell kindly prepared the illustrations.

GEOLOGICAL SETTING OF THE ORE DEPOSITS

The Eastern Cordillera of central Bolivia is composed largely of folded Paleozoic sedimentary rocks with a north to northwest trend. Shale and sandstone are the dominant rock types, but a distinctive graywacke formation occupies several parallel belts in the Llallagua-Oruro region. In the Potosi district, the folded Paleozoic formations are overlain unconformably by a volcanic complex, which includes plant-bearing tuffs of middle(?) Tertiary age. Small stocks of altered quartz porphyry are found at Potosi, Llallagua

and Oruro; only narrow dikes occur at Huanuni and Morococala. The intrusives are cut by the tin and tin-silver veins. The Potosi stock intrudes the plant-bearing tuffs; this affords the only direct means of dating the igneous activity and associated mineralization of the Eastern Andes. Late(?) Tertiary volcanics that are only slightly disturbed occupy a broad area in the Cordillera. These are definitely later than the ore deposits.

POTOSI DISTRICT

The geological formations of the Potosi region are given in Table 1, and their distribution is indicated on the accompanying map and cross-section (Figs. 2, 3).

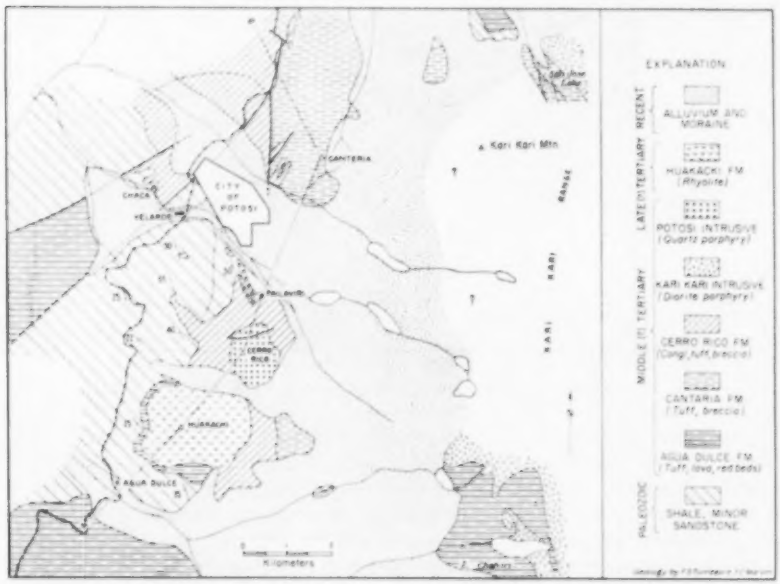


FIG. 2. Geologic map of the Potosi district.

Paleozoic and Mesozoic Rocks

The oldest formation of the Potosi district is of Ordovician age (8, p. 21) and consists of shale with a minor quantity of sandstone. The shale is slightly metamorphosed and is more accurately described as phyllite or argillite; the sandstone in places grades into quartzite. Although locally crumpled, the beds generally strike northwest and dip gently southwest.

In the vicinity of Miraflores, 15 km north of Potosi, the Paleozoic rocks are overlain by the Puca formation (64). The basal member, a cross-bedded sandstone some 700 m in thickness, is overlain by a section of 100 m com-

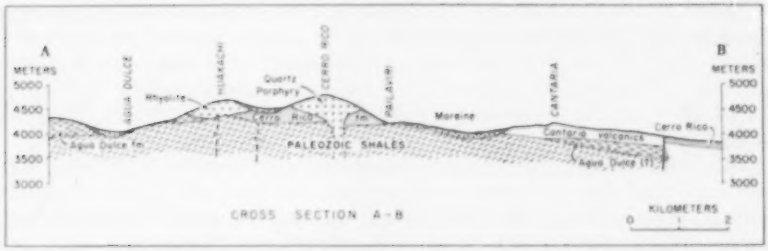


FIG. 3. Generalized cross-section, Potosi district.

posed of calcareous sandstone, marl and limestone with an upper Cretaceous fauna. Above this section are alternating beds of marl, mudstone and sandstone having a total thickness of 1,800 m, the upper part of which may be of early Tertiary age.

Middle(?) Tertiary Volcanic Rocks

The volcanic complex of middle (?) Tertiary age includes agglomerate, coarse breccia, tuff and lava, together with minor shale and sandstone. In a preliminary review of the district (74), the volcanic sequence was divided into two units, but more recent study (49) indicates that a threefold division is preferable.

TABLE 1

GEOLOGIC COLUMN, POTOSI DISTRICT

Age	Formation		Thickness (meters)
Late (?) Tertiary	Huakachi rhyolite		250+
Middle (?) Tertiary	Potosi stock. Quartz porphyry. Cuts the Caracoles tuff. Relation to the Kari Kari stock unknown		
	Kari Kari stock and breccia. Diorite porphyry. Cuts the Agua Dulce and Canteria formations. Not in contact with the Cerro Rico formation		
	Cerro Rico formation	Caracoles tuff	300+
		Venus breccia	0–100
		Pailaviri conglomerate	10–170
	Canteria formation		350+
	Agua Dulce formation		450
Early Tertiary–Late Cretaceous	Puca formation. Exposed at Miraflores; absent in Potosi district		—
Ordovician	Shale (argillite) and sandstone (quartzite)		1500+

Agua Dulce Formation.—The Agua Dulce formation is well exposed in the Kari Kari Range and extends 15 km or more west of Potosi, where it locally rests on the Puca formation. It has a much greater lateral extent than the succeeding formations but is absent in the immediate vicinity of Cerro Rico, where the younger volcanic formations overlap the Paleozoic beds.

The basal member of the Agua Dulce formation consists of red shale, red and buff sandstone and fine conglomerate. This is overlain by distinctive andesite flows which contain abundant feldspar phenocrysts. Andesitic tuff, glassy flows and coarse breccia are subordinate rock types.

Canteria Formation.—A series of volcanic rocks ranging from rhyolite to quartz latite and dacite is referred to as the Canteria formation named after Canteria Ridge (76). Coarse agglomerates at the base are followed by breccias, tuffs and thin lava flows; certain tuff beds have a characteristic purple color. A noteworthy feature of the formation is the local development of red garnet as an accessory igneous mineral. Agglomerates and thin tuff beds are also found at San Jose Lake, where they are cut by intrusives of the Kari Kari Range. An intensely bleached agglomerate, which crops out on the highway on the east side of Cerro Rico, is believed to be an altered phase of the Canteria agglomerate.

Cerro Rico Formation.—The Cerro Rico formation is composed of three members, the Pailaviri conglomerate, the Venus breccia and the Caracoles tuff. The Pailaviri conglomerate (23) at the base of the section ranges in thickness from 70 to 170 m in the mine area. Although it thins to the north and south, it has been traced as far as 10 km from the Cerro. The pebbles includes shale and quartzite, as well as igneous rocks derived from the Agua Dulce and Canteria formations; the finer matrix locally exhibits distinct bedding.

In the Venus adit, the Pailaviri conglomerate is succeeded by the Venus breccia, composed of angular fragments of igneous and sedimentary rocks set in a tuffaceous matrix. This member reaches a thickness of 100 m but is found only on the northeast slope of Cerro Rico. In the Purisima adit there seems to be a gradation between garnet-bearing breccia of the Canteria type and a bleached breccia identical with that of the Venus adit (49).

The Pailaviri conglomerate is commonly overlain by the Caracoles tuff, which has an exposed thickness of 300 m. It consists of well-bedded ash, with intercalated layers of breccia, fine conglomerate and sandy material.

Abundant plant remains are found in the Caracoles tuff. Berry (7, 8) classified the flora as late Pliocene, whereas Steinmann (70) and Brüggen (12, p. 91) considered it to be distinctly older, not later than Miocene and possibly as old as late Eocene. A middle Tertiary age (late Eocene to early Miocene) seems to be consistent with the geologic history of the Andes, and the volcanics are so designated in the table.

Distribution.—The distribution of the volcanics within the district is highly irregular, and each of the volcanic formations may rest directly on the Paleozoic beds. Many of the smaller units are of local character; others show pronounced lateral change in lithology. Unconformities within the

section are difficult to evaluate. The one at the base of the Canteria formation is probably the most important, as the underlying Agua Dulce formation has been completely eroded in the mine area.

Middle(?) Tertiary Intrusive Rocks

The intrusive igneous rocks of middle(?) Tertiary age include the stock of Kari Kari, the intrusive of Potosi, the associated dikes of Cerro Chico, and small bodies of breccia exposed in the lower levels of the mine.

Kari Kari Stock.—The rugged Kari Kari Range, extending from San Jose Lake southward to Andacaba, is dominated by a large irregular body of diorite porphyry (39, 59). At Chalviri Lake east of Potosi, the main stock intrudes the Agua Dulce lavas; at San Jose Lake, dikes and sheets of porphyry cut the Canteria agglomerate (Fig. 2).

The typical intrusive contains abundant plagioclase phenocrysts set in a fine-grained groundmass. Phenocrysts of potash feldspar are less common; quartz is comparatively rare. The rock is described as rhyodacite by Kozlowski and Smulikowski (41) but is classed as diorite porphyry by Heinrich (32). An abundance of red garnet as a pyrogenic mineral not only reflects a contamination of the magma but also indicates a close genetic connection between the Kari Kari intrusions and the garnet-bearing volcanics of the Potosi district. Reconnaissance in the Kari Kari Range itself also discloses cross-cutting bodies of breccia and superficial igneous rocks related to the diorite stock. It seems likely, therefore, that the Kari Kari Range was the site of several episodes of volcanism and was the principal source of the volcanics of the Potosi district.

Potosi Stock.—The main intrusive body of Potosi rapidly decreases in size with depth. At the surface the intrusion occupies an oval area 1,700 m in length and 1,200 m in width, but on the lower mine levels it passes into a dikelike body only 100 m across (Fig. 3). The intrusive cuts the folded Paleozoic formations and the overlying Cerro Rico volcanics. Near the base of the volcanic formation, the porphyry widens out to form the mushroom-like mass, and along the margin of the intrusion, the volcanics, which normally dip at low angles, become steeply inclined and locally overturned (Fig. 15).

The porphyry is intensely altered, but study of thin sections suggests that the original rock was probably dacite or quartz latite (34, p. 55). Intense silicification has affected the entire upper portion of the porphyry body; sericitization is more prominent in depth.

The shape of the Potosi intrusive might suggest a volcanic vent and associated crater, but through many kilometers of underground workings, the porphyry shows no fragments whatever. Three or four small bodies of coarse breccia are known, but these are not sufficient in size or number to support the view that the intrusive as a whole represents a volcanic vent. Two dikes of altered porphyry similar to the stock of Cerro Rico crop out on Cerro Chico, a northerly spur of the main peak (Fig. 2).

Breccia Dikes in Argillite.—In the lower mine levels, the massive argillite of Paleozoic age is cut by a few dikelike bodies of breccia that contain some

fragments of nonporphyritic igneous rock as well as numerous shale fragments. Whether the breccia dikes are genetically related to the Potosi stock or to the older flat-lying volcanics is unknown.

Late(?) Tertiary Volcanic Rocks

The Huakachi rhyolite, covering a roughly circular area to the south of Cerro Rico, consists of tuff and breccia with minor flows, all containing abundant quartz. The formation does not come in contact with the Potosi stock, but cobbles of pyritized porphyry enclosed in the rhyolite demonstrate its post-mineral age. It is interpreted as an outlier of the Pliocene(?) volcanics that occupy the main divide west of Potosi (3, p. 223–228).

LLALLAGUA-ORURO REGION

Paleozoic Formations

In the Llallagua-Oruro region, Paleozoic sedimentary formations prevail except where capped by late Tertiary volcanics. The stratigraphic section first described at Llallagua has now been recognized in other districts and this permits a preliminary regional correlation (Table 2).

Llallagua District.—The Paleozoic formations at Llallagua, described briefly by Deringer and Payne (21) and Moon (54), consist of nearly 2000 m of sedimentary rocks (Table 2). The Cancañiri graywacke, the oldest

TABLE 2

LLALLAGUA–ORURO REGION. PALEOZOIC FORMATIONS

Thickness in Meters

Llallagua	Morococala	Huanuni	Morococala Road
Ventilla shale 250+			
Catavi sandstone 50			Sandstone 250+
Pampa shale 750	Shale 1,000+	Black shale 300+	Shale 2,000 (?)
		Brown shale 400	
Llallagua Fm. Sandstone, minor shale 250	Sandstone 250–300	Sandstone, minor shale 500	Sandstone 250
Absent	Absent	Micaceous sandstone and phyllite 0–90	Absent
Cancañiri graywacke 650+	Graywacke 700+	Graywacke 300+	Graywacke 500+

formation of the district, occupies the axis of the Llallagua anticline and forms a belt 1,300 to 1,500 m in width (Fig. 4). The fresh rock is dark gray, but oxidation of scattered pyrite gives the weathered surface a rusty brown tone. The graywacke is further distinguished by its massive appear-

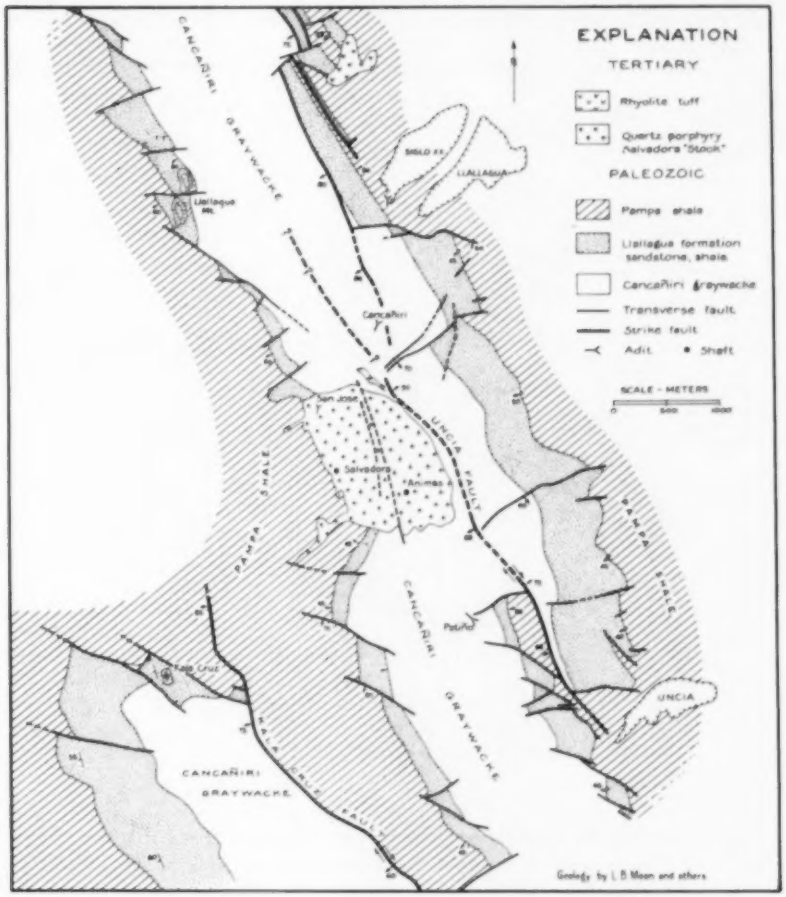


FIG. 4. Geologic map of the Llallagua district.

ance, finely fragmental character and spheroidal weathering. It is overlain unconformably by the Llallagua formation, which consists of coarse massive sandstone at the base, followed by alternating beds of sandstone and shale. The sandstone forms a series of bold outcrops which extend northwest and southeast of Llallagua.

The Pampa formation is composed almost entirely of thin-bedded, brown shale but contains a few beds of sandstone. The Catavi sandstone, which overlies the Pampa shale, contains a fauna of Devonian age (38). Its thickness is only 50 m but elsewhere a sandstone occupying the same stratigraphic position reaches a thickness of 250 m. The dark gray Ventilla shale is followed by red conglomerate and red shale which define the trough of a broad

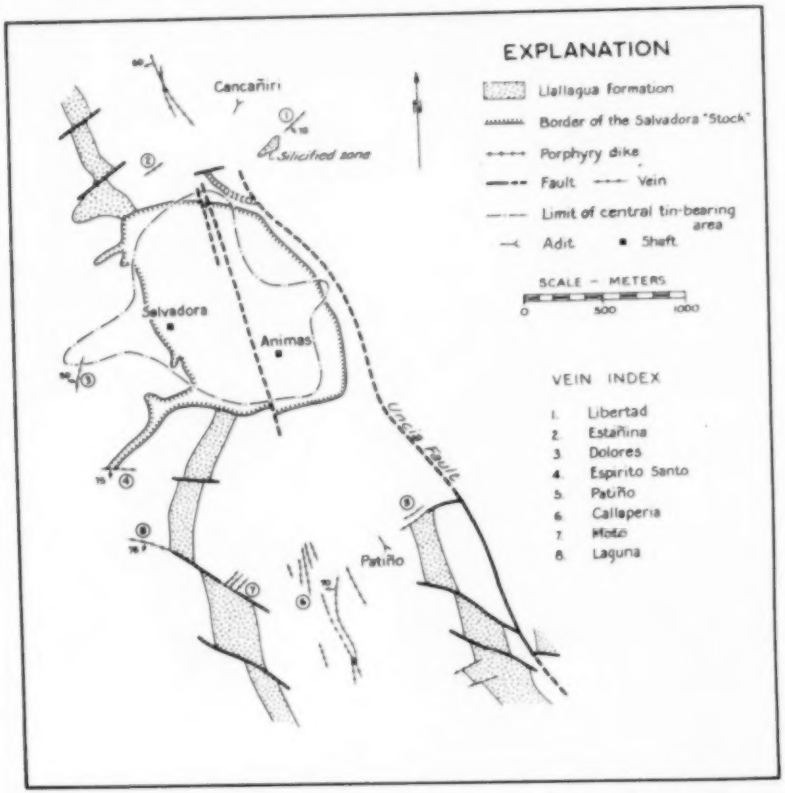


FIG. 5. Llallagua district. Central tin-bearing area and veins of the outer zone.

syncline east of Siglo XX. The red beds may be of Cretaceous age, comparable to the Puca formation, or they may be late Paleozoic, equivalent to certain red beds of the Cordillera Real.

Regional Features.—The Paleozoic section of the Huanuni-Morococala region consists largely of shale but includes two prominent sandstone formations, the lower resting on graywacke (Fig. 6). In the Morococala district, two major anticlines are marked by belts of graywacke bordered by sand-

stone (Fig. 7). The graywacke occupies another belt to the southwest and crops out in two raised fault blocks along the Huanuni anticline (Fig. 6). The two Morococala belts projected to the southeast probably appear in the Llallagua district, but a considerable part of the intervening area is covered by late Tertiary volcanics.

The main sandstone formation of Huanuni, which has a thickness of 500 to 600 m, occupies a broad irregular belt along the Huanuni anticline. Like the sandstone at Morococala, it is underlain by graywacke, and both formations correlate with the Llallagua sandstone (Table 2). South of the Huanuni River, an unconformity between the graywacke and overlying

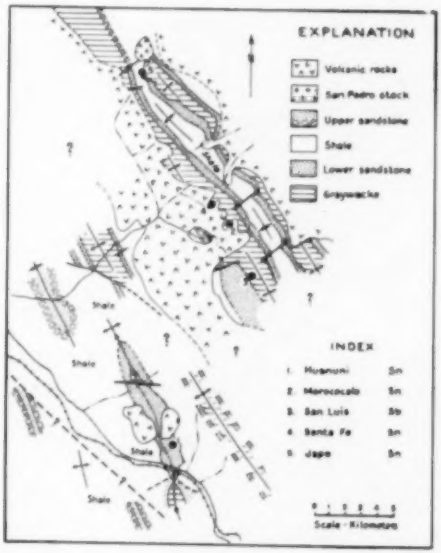


FIG. 6. Sketch map of the Huanuni-Morococala region.

sandstone is demonstrated, as the sandstone locally rests on phyllite and micaceous sandstone, beds that elsewhere were eroded before deposition of the graywacke (Fig. 8).

The basal sandstone of the Morococala-Huanuni region is overlain by a thick shale formation, and this is followed by a second sandstone, the latter forming prominent ridges south and west of Huanuni (Fig. 6). The general sequence of beds agrees with that at Llallagua, but formations differ in thickness and precise correlation is impossible. In the area west of Morococala, the graywacke has not been identified, and the shale series of Oruro must occupy a relatively high stratigraphic position.

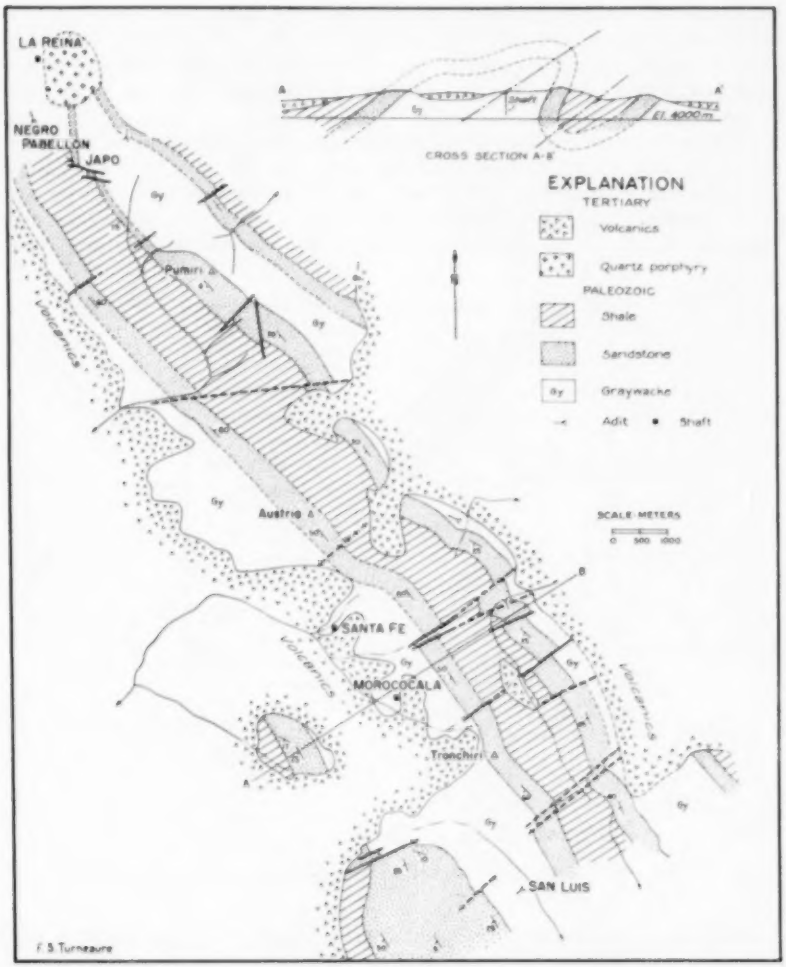


FIG. 7. Geologic map of the Morococala district.

Middle(?) Tertiary Intrusive Rocks

Quartz Porphyry.—At Llallagua and Oruro intrusive activity is evidenced by stocklike bodies of porphyry, whereas at Morococala and Huanuni intrusive igneous rocks are restricted to a few narrow dikes. The igneous rocks as a group probably correlate with the Potosi stock which intrudes the plant-bearing beds of middle(?) Tertiary age.

The main intrusive body of Llallagua, the Salvadora "stock," represents a volcanic vent. As exposed in outcrop, the intrusive measures 1,730 by 1,050 m, but on the 650-meter level the dimensions are reduced to 1,000 by 700 m (Figs. 4, 12). Several narrow dikes of quartz porphyry also occur at Llallagua, most of them having a northwest trend (Fig. 5).

The Salvadora intrusive is made up of porphyry and porphyry breccia, the latter containing numerous small fragments of the older sedimentary rocks. There is no evidence to indicate that one type of porphyry is consistently older than the other; the two comprise essentially a single porphyry mass. This is highly altered throughout, with the introduction of sericite, quartz and tourmaline. The original rock was probably a quartz latite

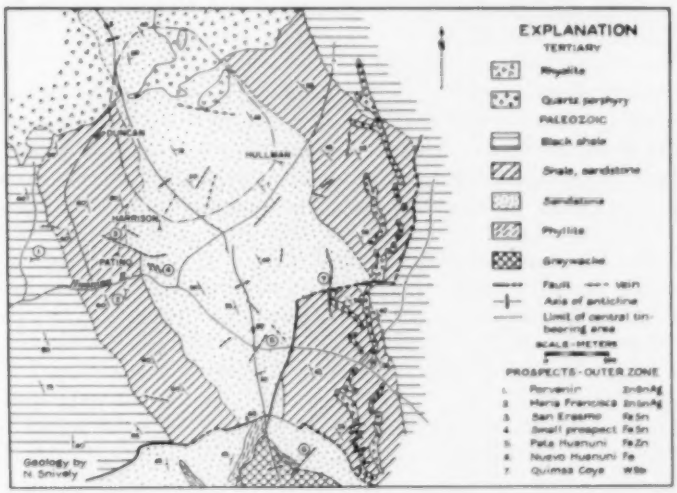


FIG. 8. Geologic map of the Huanuni district showing the central tin-bearing area and veins of the outer zone.

porphyry (71, p. 19). The large volume of breccia, the slight degree of contact alteration, and the form of the porphyry body support the view that the Salvadora intrusive is an explosive vent. Superficial volcanics that might be attributed to the vent have not been preserved in the district.

The largest intrusive of the Oruro district, according to Chace (19, p. 344), is the San Pedro stock, but the ore deposits are associated with the smaller intrusives of San Jose and Itos. The San Jose stock at the surface measures 1,700 by 1,000 m and the Itos stock is 1,800 by 1,500 m. In depth the San Jose intrusive passes into three dikelike bodies, the most important having a width of 200 m and a minimum length of 600 m. The altered intrusives, characterized by sericite, pyrite, kaolinite and secondary quartz, are classified by Chace (19, p. 436) as quartz latite porphyry. Sev-

eral quartz latite flows cover a small area near the east margin of the San Jose stock. The flows "appear to grade into massive porphyry which in depth is known to be intrusive" (19, p. 351). This indicates that the intrusives of Oruro, like those of Llallagua and Potosi, are of shallow-seated character.

Three altered dikes of quartz porphyry are found along the eastern margin of the Huanuni district. They have a northerly trend, but short segments and tongues strike northeast. Occupying a zone of 250 m, the individual dikes are roughly parallel and average 35 m in width (Fig. 8). In the Morococala district, three or four narrow porphyry dikes cut the Paleozoic shale; one altered dike of northwest strike is well exposed in the workings of the Morococala mine, where it is cut by the tin-bearing veins. The stock of San Pablo, at the northwest corner of the district, is of oval outline and some 1,200 m across (Fig. 7). The rock is well altered and similar to the intrusives of the other districts.

Intrusive Breccias.—Cross-cutting bodies of altered breccia that contain igneous fragments are well developed at Llallagua and Oruro and are also recognized at Morococala. The common type of breccia at Llallagua is composed of angular fragments of porphyry with smaller fragments of sedimentary rocks, all set in a finely fragmental matrix. Containing abundant tourmaline, the matrix generally has a dark gray color (71, p. 19). The coarse breccia occurs as irregular bodies up to 50 m across and as dikes cutting the light porphyry. Many small cracks in the porphyry are filled with fine breccia composed mostly of pulverized rock material.

The prominent breccia of Oruro, the San Jose breccia, consists of fragments of quartz latite porphyry and dense argillite in a matrix of fine rock material (19, p. 353–356). It forms irregular pipes and dikelike bodies up to 600 m in length. The larger bodies of breccia occupy the margin of the San Jose stock, but smaller lenses and dikes cut the argillite as well as the porphyry.

Breccia with igneous material has not been found at Huanuni, but one breccia body is exposed in two drifts of the Morococala mine. The stock of San Pablo is also accompanied by dark breccia containing fragments of porphyry set in a dark tourmalinized matrix.

The breccias of Llallagua were probably formed by explosive activity connected with the development of the Salvadora vent, and Chace (19, p. 356) attributes the San Jose breccia to explosive action. In both districts the breccias were formed after emplacement of the porphyry. The fine breccia, probably mixed with water to form a mudlike fluid, was highly mobile and penetrated many fractures and cracks in the porphyry.

At Llallagua and Huanuni another type of breccia occurs, the fragments of which are composed exclusively of altered sedimentary rocks. This breccia, closely related to the mineralization, is described in connection with the ore deposits.

Late(?) Tertiary Volcanics

A flat-lying volcanic formation composed of andesitic and rhyolitic tuff caps some of the summits at Llallagua and Huanuni and covers fully half the Morococala district, where it reaches a thickness of 90 m. It represents a part of the widespread volcanic formation of Pliocene(?) age. Some of the oxidized veins of the Santa Fe mine at Morococala are covered by unaltered tuff, which is definitely of post-mineral age.

STRUCTURAL GEOLOGY

In reviewing the structural geology, a division has been made between features of a regional type that predate the porphyry, and the vein fractures and other structural elements that belong to a late period of stress following igneous activity.

REGIONAL STRUCTURE

General Description

Folds.—The Andean structure is best displayed by the folded Paleozoic formations which have a north to northwest trend. In the mining districts the average strike of the sedimentary formations ranges from N to N 35° W (Table 3). Some folds are asymmetrical with axial planes inclined to the east or west. At Llallagua and Morococala, the fold axes are nearly horizontal, but the Huanuni anticline has the form of an elongated dome. The major folds are readily traced by the sandstone beds that cap the high ridges, whereas the soft shale formations occupy the lower slopes and broad valleys.

Faults.—Regional transverse faults are most abundant and usually they can be divided into several strike groups. Longitudinal faults probably constitute an important part of Andean structure, but they have been noted in only a few places. Dike trends are significant as they may provide a clue to the pattern of early fracturing. Most faults of the regional type are believed to be of early age, but a few cut the porphyry and belong to a late period of stress (Table 3).

The Llallagua anticline, which has been mapped by staff geologists (21, 54), is of complex character and is offset by many transverse faults (Fig. 4). Moon (54, p. 69) distinguished three strike groups among the transverse faults, but in the present analysis only two groups are recognized, one striking N 70° W and the other N 66° E (Fig. 9; Table 3). The northwest faults consistently offset those of northeast strike and produce a greater displacement of the sandstone beds. The northwest faults show left-lateral movement whereas the pattern of northeast faults is variable. The dip observed on 15 transverse faults ranges from 65° to vertical. Three longitudinal faults (N 31° W) north of Siglo XX are cut by transverse faults and seem to be of early age. The prominent Uncia and Kala Cruz faults (N 33° W) are of late age and are described in connection with the vein frac-

TABLE 3

STRUCTURAL ELEMENTS OF REGIONAL TYPE

District	Elements	No.	Northeast		North		East		Northwest	
			No.	Average	No.	Average	No.	Average	No.	Average
Potosi	Regional strike[1]									N32W
	Dikes	2							2	N26W
	Faults, early	5	3	N57E	2	N3E				
	Faults, late	4			4	N6E				
Llallagua	Anticline									N30W
	Dikes	9							9	N27W
	Faults, early	60	37	N66E			20	N70W	3	N31W
	Faults, late	13	5	N44E			5	N74W	3	N33W
Morococala	Anticline									N35W
	Dikes	1							1	N40W
	Faults, early	31	26	N59E			5	N75W		
Huanuni	Anticline					N15W				
	Dikes[2]	18			15	N10W	3	N74E		
	Faults, early	7			3	N10E	3	N85E	1	N67W
	Faults, late	6					6	N74E		
Oruro	Regional strike[3]					North				
	Dikes	11			2	N3W	2	N85W	7	N44W
	Elongated stocks	2	1	N22E					1	N48W

[1] Strike of Tertiary volcanics.
[2] Two dikes intruded as 18 short segments.
[3] Strike of Paleozoic formations in Iroco Hills.

tures. The transverse faults of N 74° W strike are probably branches of the Kala Cruz fault.

The sandstone beds of Morococala are likewise offset by numerous transverse faults of steep dip (Figs. 7, 9). The principal set strikes N 59° E; a minor set strikes N 75° W (Table 3). Five northeast faults cross sandstone belts having different angles of dip; these faults show total displacement ranging from 90 to 310 m, with both vertical and horizontal movement. The Pairumani fault west of Morococala is of uncertain age. It has a strike of N 68° W and shows an offset of 2,500 m or more (Fig. 6).

Two transverse faults of easterly strike (N 85° E) cross the Huanuni anticline, one on the high ridge south of the Huanuni River and the other some 3 km north of the mine area (Figs. 6, 8). The sandstone formation on the two limbs of the anticline exhibits an extreme difference in thickness, and the beds along the axial plane show an abrupt reversal in dip. These facts suggest major thrust faulting along the axis of the fold although the planes of movement cannot be identified. Vertical adjustments also took place along two sets of early fractures (N 10° E, N 67° W); minor faults (N 74° E) of late age displaced the porphyry dikes (Table 3).

Only a few faults have been mapped at Potosi, those of principal importance striking N 57° E. One prominent fault of N 3° E strike is dis-

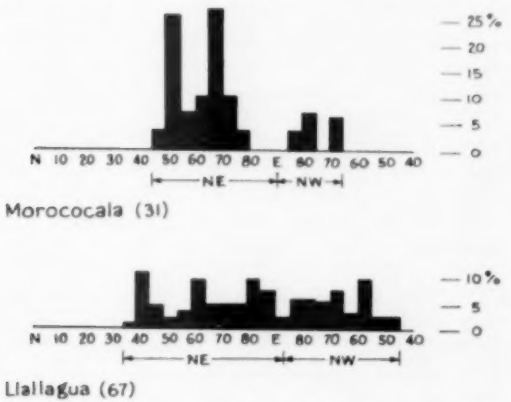


FIG. 9. Regional structure. Strike distribution of transverse faults in five-degree units.

placed by a northwest fault. Pre-mineral movement along vein fractures that cut the intrusive defines a set of late faults (N 6° E).

In the Oruro district, where intrusive igneous rocks generally prevail at the surface, major faults of the regional type have not been identified. The principal indication of an early fracture system is the trend of dikes and narrow lenses of intrusive breccia.

Stress Analysis

The pronounced folding of the Paleozoic formations, which gave rise to the succession of anticlines and synclines, is evidence of shortening of the crust perpendicular to their trend, with compression acting in a NE-SW direction. In the Potosi district, a discordance can be noted between the Tertiary volcanics and the Paleozoic shales and sandstones, whereas at Miraflores north of Potosi, the Cretaceous (Puca) beds dip almost as steeply as the underlying Paleozoic formations. This indicates two or more periods of folding, the most pronounced being in early(?) Tertiary time, after deposition of the Puca formation. Folding was resumed at a later stage, as the middle(?) Tertiary volcanics are somewhat deformed. The principal folding preceded the main period of intrusion; the intrusive rocks show no stress effects, and the Potosi stock cuts the Tertiary volcanics that were deposited after the main period of deformation.

Faults developed during the main period of folding are characteristic of most orogenic belts. Several types of faults may be recognized, all showing a consistent relationship to the fold axes (6, 9, 22). Many of the early regional faults of the Bolivian Andes seem to be related to the folds, and with maximum stress oriented perpendicular to the folds in each district, the observed fault pattern agrees reasonably well with theoretical requirements (Table 4).

TABLE 4

EARLY PERIOD OF STRESS. ANALYSIS OF REGIONAL STRUCTURE

District	Elements	No.	Tension[a]		Shear-1		Shear-2		Compression	
			No.	Strike	No.	Strike	No.	Strike	No.	Strike
Potosi	Ideal	—	—	N58E	—	N13E	—	N77W	—	N32W[b]
	Faults	5	3	N57E	2	N3E				
	Dikes	2							2	N26W
Llallagua	Ideal	—	—	N60E	—	N15E	—	N75W	—	N30W[b]
	Faults	60	37	N66E			20	N70W	3	N31W
	Dikes	9							9	N27W
Morococala	Ideal			N55E		N10E		N80W		N35W[b]
	Faults	31	26	N59E			5	N75W		
	Dike	1							1	N40W
Huanuni	Ideal	—	—	N75E	—	N30E	—	N60W	—	N15W[b]
	Faults	7	3	N85E	3	N10E	1	N67W		
	Dikes	18	3	N74E					15	N10W
Oruro	Ideal			N90E		N45E		N45W		North[b]
	Stocks	2			1	N22E	1	N48W		
	Dikes	11	2	N85W			7	N44W	2	N3W

[a] Extension (tension) failure; direction of maximum stress.
[b] Trend of folds; basis of stress orientation.

Major overthrusts have not been identified in the mining districts, but three longitudinal faults (N 31° W) that cut the overturned limb of the Llallagua anticline north of Siglo XX are interpreted as high-angle thrusts of moderate displacement. Longitudinal faults and fractures of the tension type may owe their origin to the bending of competent beds along an anticline, or they may form at a later stage with relaxation of compressive stress. Tension fractures of this kind may be occupied by some of the dikes that parallel the folds.

Faults perpendicular to major folds may reflect a stretching of the belt parallel to the fold axis and are comparable perhaps to extension fractures. Faults of this origin are probably represented at both Llallagua and Morococala by the strong northeast faults (N 66° E, N 59° E). These show considerable displacement, with both horizontal and vertical components.

In some orogenic belts, prominent faults with strong strike-slip movement transect the folds at an oblique angle. They owe their origin to shear components of compressive stress, and their effect is an extension of the fold structure. Theoretically two conjugate sets of nearly vertical faults should appear, but in field examples, only one set of faults may be developed and dips as low as 70° are not uncommon (6, p. 59–111). The early faults of N 70° W and N 75° W strike at Llallagua and Morococala are believed to be of this nature. They probably have a steep dip and show left-lateral displacement, which is consistent with the theoretical direction of compression.

In the Huanuni district, vertical movement along several faults has

produced a complex pattern of rock distribution. The two principal faults (N 85° E) are about perpendicular to the Huanuni anticline. They define a central block about 7 km in length which is structurally lower than adjacent blocks along the crest of the fold (Fig. 6). The anticline shows a reversal in plunge and is of dome-like form. The arching of a fold parallel to its axis creates tension, and this favors the development of normal cross-faults (22, p. 206–211). The two cross-faults at Huanuni are probably of this origin. Vertical movement also occurred along two faults of N 10° E strike; these are considered to be early shear planes along which later adjustments took place. Two prominent dike trends are consistent with the pattern of early fracturing.

At Potosi only a few faults of the regional type have been mapped. The most prominent strike N 57° E and appear to be of the normal type. Igneous trends at Oruro, which give the only indication of an early fracture system, agree with the orientation of folds in the nearby Iroco Hills (Table 4).

VEIN SYSTEMS AND LATE FAULTS

The ore deposits under review are all of the multiple vein type, and in each district the veins can be divided into several strike groups (Table 5; Fig. 10). At Potosi, Llallagua and Morococala, veins of northeast strike prevail and the vein patterns show marked similarities. At Huanuni and Oruro, the veins are more varied in strike and the vein groups are less well

TABLE 5. VEIN GROUPS AND POST-ORE FAULTS

District	Structural Elements	No.	NE-No. 1				NE-No. 2				North				East				Northwest			
			Strike		Dip		Strike		Dip		Strike		Dip		Strike		Dip		Strike		Dip	
			No	Aver	No	Aver	No	Aver	No	Aver	No	Aver	No	Aver	No	Aver	No	Aver	No	Aver	No	Aver
Llallagua	Central vein system (411 level)	133	66	N30E	26 26 30	74W 72E 90	31	N55E	14 15 1	70W 70S 90	9	N6W	1 8 -	66W 70E 90	5	N72E	3 2 -	70N 75S 90				
	Main veins	45	23	N30E	13 10	70W 75E	15	N53E	6 9	71W 70S	4	N5W	1 3	70W 69E	3	N72E	3 -	70N -				
	Outer zone	9									9	N12W	-	-								
	Post-ore faults	2									2	N14W	2	82W								
Potosi	Central vein system	113	74	N31E	*	75E -	17	N53E	15 2	65SE 80W	22	N6E	12 10	72E 72W								
	Upper levels	52	44	N31E	*	75E -	4	N60E	4 -	60S -	4	N7E	2 2	60E 70W					(a)	N61W	(a)	75SW 82NE
	Main veins	39	22	N30E	*	75E -	5	N55E	3 -	65SE -	14	N7E	7 7	66E 71W								
	Post-ore faults	1													1	N65E	1	70N				
Morococala	Morococala mine	62	55	N34E	*	75E -					3	N2E	3 -	75E -					4	N45W	(a)	45NE 45SW
	Santa Fe mine	-	-	N45E		?													-	N40W	-	60SW
Huanuni	Central vein system	86					24	N51E	16 4	50SW 75W	27	N9E	16 9	73W 69E	32	N79E	26 5	62S 70N	5	N41W	4 1	65NE 50SW
	Outer zone	45					10	N50E	7 3	63SE 60W	9	N5E	2 3	70W 77E	22	N65W	12 6	69S 75N	4	N46W	3 1	70NE 30SW
Oruro	West area Itos-Colorada	27	11	N25E	6 5	62E 60W					1	N11W	1 -	67E -	5	N81W	3 2	68S 60S	10	N49W	4 4	66SW 74NE
	East Area Socavon-San Jose	38					13	N55E	6 2	65SW 62SE	9	N1E	7 2	65W 72E	2	N89E	1 1	65S 75N	14	N45W	9 3	67SW 70NE
	Combined area	65	11	N25E	6 5	62E 60W	13	N55E	6 2	65SW 62SE	10	N1W	7 3	64W 70E	7	N84W	4 3	70N 63S	24	N47W	13 7	67SW 72NE

* Prevailing dip 70°-90°E, few exceptions.

(a) Minor "crossings," short strike length.

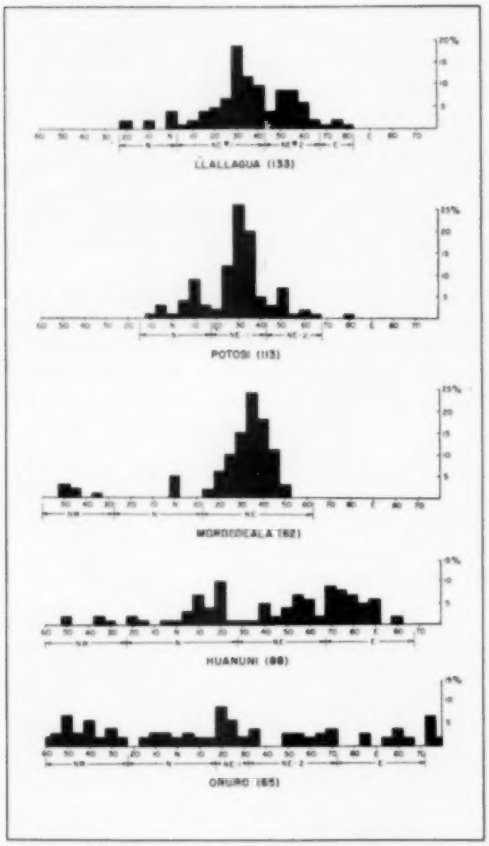


FIG. 10. Vein structure. Strike distribution of veins in five-degree units.

defined. Although certain veins in each district give evidence of displacement of a few meters, there is no indication of a significant time difference among the several vein groups.

At Llallagua, regional faulting of late age seems to have initiated the period of vein fracturing, but elsewhere faults of the regional type do not form a conspicuous part of the vein pattern. Faults of post-mineral age are notably scarce; only three of importance have been mapped in the five districts.

Description of the Vein Systems

Llallagua.—The vein pattern of Llallagua is of the lattice type, made up of four vein groups: N 30° E, N 55° E, N 6° W and N 72° E (Figs. 11, 12).

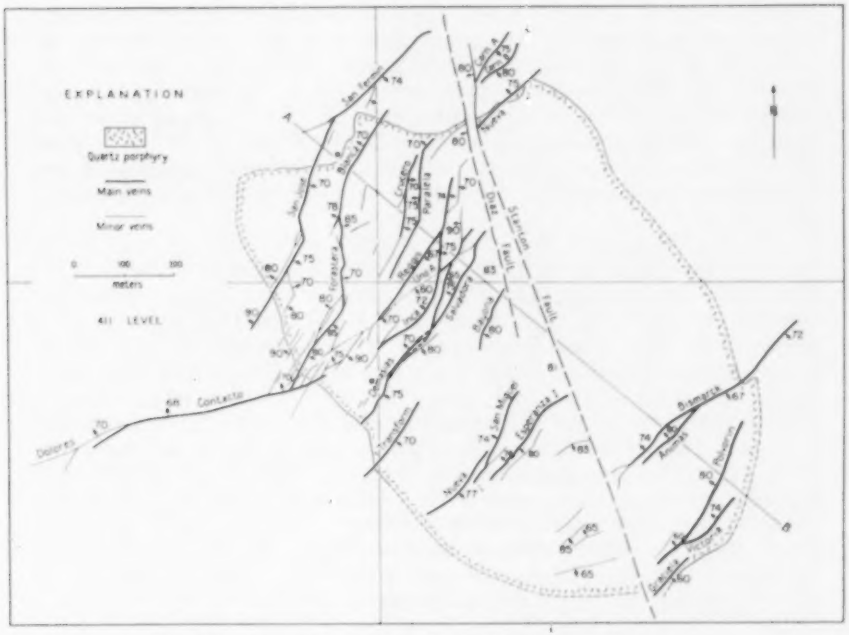


FIG. 11. Generalized plan of the Llallagua vein system.

Veins of the N 6° W group consistently dip east, but other veins show more variable but steep dips (Table 5). Veins of the N 30° E group are most numerous. The group includes several major veins, such as the San Jose and Inca-Salvadora, as well as many branch veins, narrow stringers and

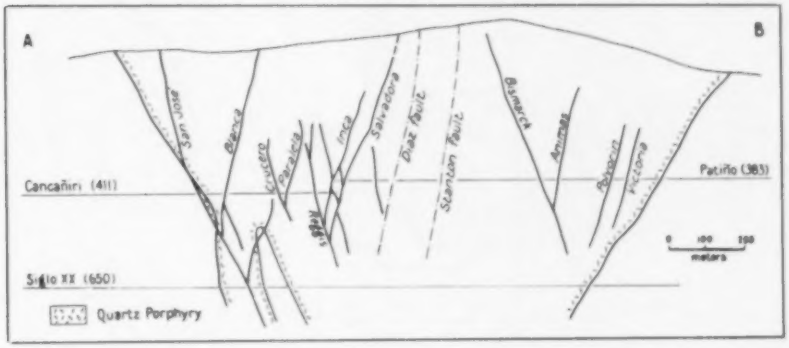


FIG. 12. Llallagua vein system. Generalized cross-section.

sheeted zones. The N 55° E vein group is exemplified by the San Fermin and Bismarck. Veins of this group give more evidence of pre-mineral movement than do those of the N 30° E group. The N 72° E vein group is identified principally by the Contacto vein, which shows considerable gouge and brecciation. Veins of the fourth group (N 6° W) are of minor importance. Two post-mineral faults strike N 14° W and dip 82° W. Most veins of the outer zone of pyritic mineralization represent mineralized regional faults, but one vein set (N 12° W) parallels the axis of the Llallagua anticline (Fig. 5).

Potosí.—The veins of Potosí, most of which strike northeast, are divided into three groups: N 31° E, N 53° E and N 6° E (Table 5). The N 6° E group includes the strong Tajo Polo-Encinas vein system with a prevailing westerly dip (Figs. 14, 15). Veins of N 53° E strike are the most productive of the lower levels (Utne system), whereas elements of the N 31° E group are more prominent in the upper part of the mine, where they make up the remarkable sheeted zone (Figs. 13, 14). This zone attains a maximum width of 175 m and is composed of countless veinlets from 1 to 5 cm in width. The veinlets are essentially parallel and dip east at a steep angle (Fig. 15). The Mendieta-Rica vein system of easterly dip borders the sheeted zone of the upper mine levels. At greater depth, major elements of this system strike more northerly and form a part of the N 6° E strike group (Fig. 13). Short veins of northwest strike are of some structural significance but of no commercial importance. The Caracoles fault of N 83° E strike and 70° N dip is of post-mineral age.

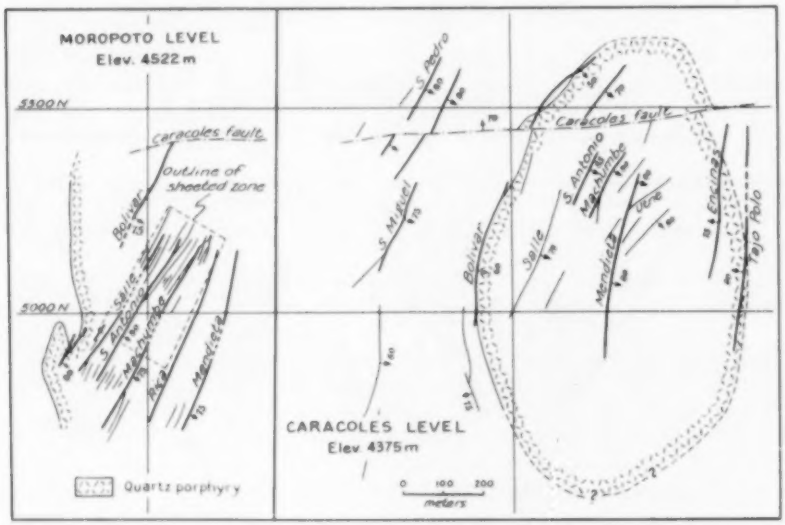


FIG. 13. Potosí vein system. Upper levels.

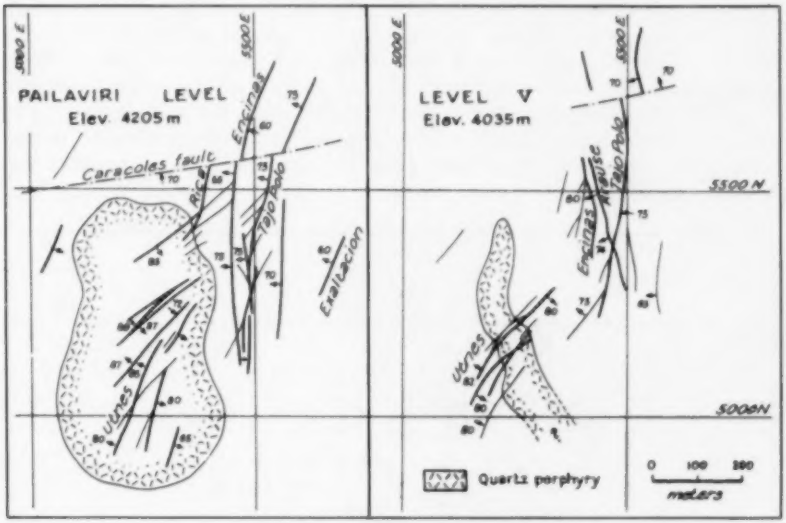


FIG. 14. Potosi vein system. Lower levels.

Morococala.—The veins of Morococala (Fig. 16) lack the persistence of those of Llallagua and Potosi. Fully 85 percent of the veins strike from N 15° E to N 50° E; they dip approximately 75° E (Table 5). The remaining veins include a minor set of N 2° E strike and steep dip, and the "crossings" or mantos (25) of N 45° W strike and low dip. At the Santa Fe mine, the major veins strike N 40° W and dip 60° SW.

Huanuni.—The Grande and Nueva veins, which have been highly productive, belong to the N 51° E strike group (Fig. 17; Table 5). Both dip to

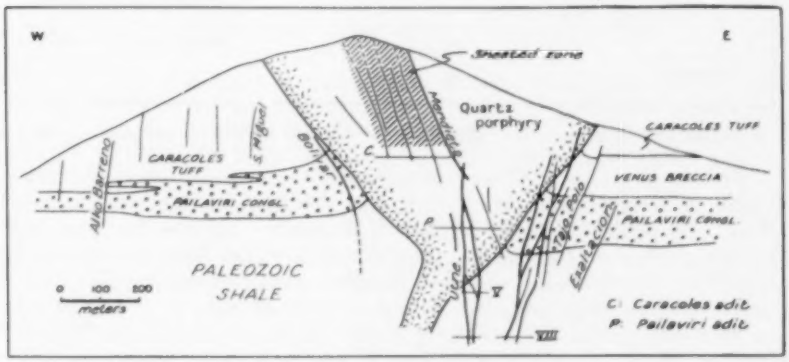


FIG. 15. Potosi vein system. Generalized cross-section.

the southeast at a low angle (40–45°). In the area to the east and northeast, the main veins simulate a lattice pattern; one set strikes N 79° E and the other N 9° E. Southwest of the Grande are several veins of the N 79° E strike group, but weak veins of N 41° W strike form the second vein set. The N 79° E veins generally dip south but the others are more variable. In the area to the north, the veins diverge considerably from average trends. Veins at the margin of the district (Fig. 8) have about the same strike distribution as those of the central zone.

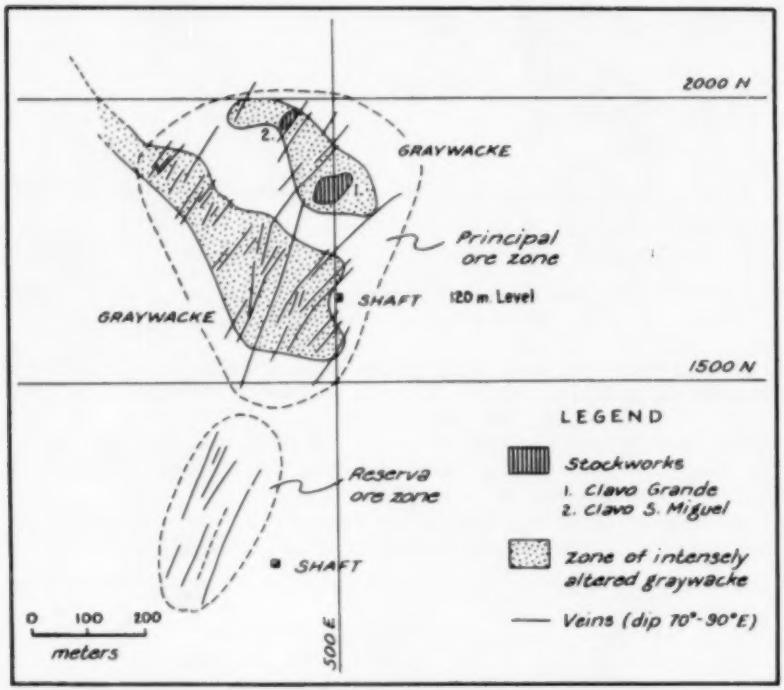


FIG. 16. Morococala mine. Zone of hydrothermal alteration and vein system.

Oruro.—The veins of Oruro, although widely distributed, are concentrated largely in certain places where they form the vein clusters described by Chace (19, p. 357). Those of greatest importance are the San Jose and Socavon clusters on the east and the Colorado and San Luis clusters on the west (Fig. 18; Table 5). There is no great concentration of veins within a narrow strike range, but there is a dominance of veins of northwest and northeast strike (Fig. 10). Veins of the N 47° W group, such as the Purisima and San Luis systems, generally dip southwest but numerous hanging-wall branches have the opposite dip. Veins of the N 23° E group are

FIG. 17. Generalized plan of the Huanuni vein system.

confined mostly to the Colorado section, whereas those of N 55° E strike are prominent in the San Jose area. There is also an indication of two minor vein groups. One strikes N 1° W as exemplified by the Quintanilla vein; the other strikes N 84° W and is represented by the strong Bronce vein.

Stress Analysis

The presence of countless veins that cut the intrusive rocks affords proof that a major period of stress followed intrusive igneous activity. Also belonging to the late period of stress are certain faults of the regional type, a few of which seem to be closely related to the vein fractures. The structural elements can be divided into several strike groups, which can be correlated with regional stress, but the variability in dip is more difficult to reconcile

with any simple stress system (Table 6). Nevertheless, both dip and strike should be taken into account in any analysis of causative stress (50, p. 179).

Morococala.—The Morococala vein system consists essentially of a single vein group having an average strike of N 34° E and dip of 75° E (Fig. 16). The veins are narrow, regular and sharply defined. They have the characteristics of tension or extension fractures, with maximum stress acting parallel to their trend. Their departure from vertical suggests that the axis of minimum stress, or direction of easiest relief, was slightly inclined (Table 6). A few short veins of N 45° W strike and low dip might be compared with small thrust faults, oriented at right angles to the pressure. The closest parallel to this type of pattern is found in the laboratory experiments described by Mead (53). A rubber sheet coated with paraffin was subjected to rotational force. Vertical conjugate shear planes and tension fractures

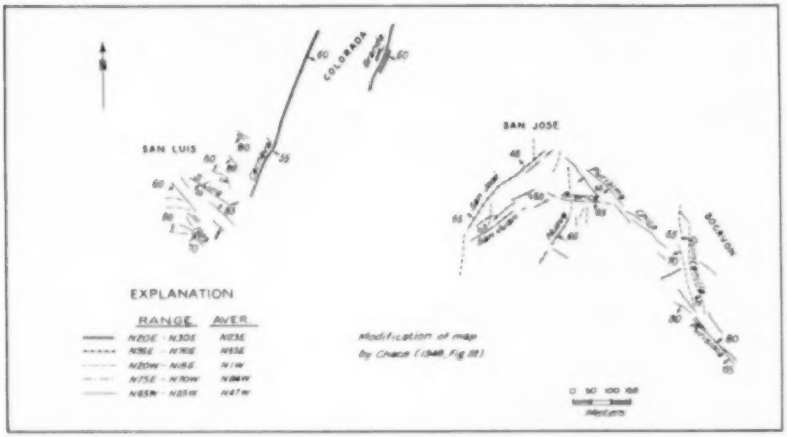


FIG. 18. Sketch of the Oruro veins showing strike groups. Typical mine level.

developed in the brittle layer, together with a few minute thrusts oriented perpendicular to the tension cracks. Perhaps the block of ground at Morococala, which consists of brittle, silicified graywacke, was fractured by similar rotational force with maximum stress oriented approximately N 34° E. One poorly developed set of shear planes may be represented by the minor veins of N 2° E strike.

Potosi.—The Tajo Polo-Encinas vein system is a dominant feature of the Potosi vein pattern and it largely defines the N 6° E vein group. The main veins dip uniformly west (70°) although a few branch veins and connecting stringers dip east. The Utne veins average N 53° E and stand nearly vertical. Although many of the individual veins are short and irregular, the Utne vein group is persistent and essentially completes the vein pattern

TABLE 6. LATE PERIOD OF STRESS. ANALYSIS OF VEIN FRACTURES

District	Vein Group	Type of Fracture	Vein Record Strike	Vein Record Dip	Angle T-S	Plunge of Intermediate Stress Axis	Pitch of Max. Stress[1]	Calculated Plane of Rupture Type	Calculated Plane of Rupture Strike	Calculated Plane of Rupture Dip	Vein Group[2] Strike	Vein Group[2] Dip	Notes
Potosí	Tajo Polo	Shear 1	N6E	72W									
	Utne	Tension	N53E	65SE	51	62 S44W	28NE	S_2	N76W	65S	-	-	S_2 not represented
	Tajo Polo	Shear 1	N6E	72W									
	Utne	Shear 2	N53E	65SE	26	62 S44W	27NE	T	N30E	62W	N31E	75E	Dip reversed
	Mendieta	Shear 1	N6E	72E									
	Utne	Shear 2	N53E	65SE	24	70 N66E	16SW	T	N30E	76E	N31E	75E	Good correlation
Oruro	Purisima	Shear 1	N45W	67SW									Main veins dip S; minor veins dip N
	San Jose	Shear 2	N55E	65NW	46	55 N62W	34E	T	N85W	69N	N84W	63S	
	Nueva	Shear 1	N1W	64W									Possible minor stress system
	Minor set	Shear 2	N84W	70N	44	57 N50W	6NE	T	N50E	58NW	N55E	65NW	
Llallagua	Grande-Clavo East group	Tension	N51E	50SE							N10E	55E	Veins near Grande.
		Shear 1	N79E	62S	26	46 S66E	18SW	S_2	N16E	47E	N5E	75W	Main veins north group
Morococala	Main veins	Tension	N34E	75E									Maximum stress is nearly horizontal
	Minor set	Shear 1	N2E	75E	31	74 S73E	48W	-	-	-	-	-	
	Uncia fault N55°E group	Shear 1	N25W	90									Early stage; tension not represented
		Shear 2	N55E	(3)	40	90 -	Hor.	T	N15E	90	-	-	
	N30°E group	Tension	N30E	(4)									Late stage gravity control[5]
	Minor group	Shear	N6W	(4)	36	Hor. N30E	Vert.	-	-	-	-	-	

(1) Pitch measured in plane of extension (tension) fractures.

(2) Vein group to be compared with calculated plane of rupture.

(3) Variable steep dip, early stage regional stress.

(4) Variable dip related to gravity control.

(5) Gravity control; maximum stress vertical, intermediate stress in N 30°E plane.

of the lower levels (Fig. 14). The Utne elements suggest tension breaks, whereas the stronger, more regular veins of the Tajo Polo type may represent shears (Table 6). The true angle between the two vein sets is 51°, which is greater than the usual angle between shear and tension fractures. This stress orientation, however, is favored as it seems consistent with vein characteristics. Moreover, the angle of 51° is not a precise figure as it is based upon average dip and strike; the true angle between certain major veins of the two groups on the lower levels is as low as 40°. The line of intersection of the two vein sets, the intermediate axis of the stress ellipsoid, plunges 62° SW (S 44° W).

The N 31° E vein group includes the narrow veins of the sheeted zone as well as several persistent veins of the upper levels. Veins of the group consistently dip east at 75°. The strong Mendieta-Rica vein system, which borders the sheeted zone, belongs to the N 6° E vein group, but unlike the Tajor Polo, it dips to the east (72°). The complex of veins of easterly dip of the upper levels merges in depth with the transverse Utne vein system (Figs. 13, 14). Angular relations in plan suggest that the N 6° E vein group (Mendieta-Rica) and N 53° E vein group (Utnes) may represent shear planes, whereas the N 31° E vein group may correspond to tension fractures. This interpretation is strengthened by the distinctive character of the N 31° E vein group; it is made up mostly of narrow, parallel veins with sharply defined walls, comparable to the narrow veins of Morococala.

On the assumption that N 6° E and N 53° E vein groups represent conjugate shears, the plane of tension failure bisecting the angle between the two shear planes should strike N 30° E and dip 78° E (Table 6). This calculated plane of rupture agrees closely with the attitude of the sheeted zone, N 31° E and dip of 75° E. The line of intersection of the three planes has a plunge of 70° NE (N 66° E).

Although the analysis presented is far from precise, it does suggest that a stress system of the general type proposed may, indeed, account for the Mendieta-Rica and associated vein systems and for the change in pattern with depth. The stress orientation, however, differs considerably from that of the Tajo Polo system. This difference may be a reflection of contrast in bed rock geology of the two areas, or more likely it may signify a change in stress during an extended period of fracturing. Deformation started, perhaps, with the formation of the Tajo Polo system and the Utne group; it continued under modified stress conditions with development of two vein systems of easterly dip and a reopening of the Utne fractures.

The sheeted zone of N 31° E strike is marked by a few narrow veins of N 61° W strike, not unlike the crossings at Morococala. The Potosi veins, however, generally have a steep dip (70–90°). A possible explanation is that with continued fracturing, the force of gravity became dominant and the direction of maximum stress approached the vertical. With maximum stress inclined, at say 60°, small vertical shears might appear, comparable to normal faults produced by vertical forces.

The Caracoles fault strikes N 83° E and dips 70° N. Its attitude is at variance with the stress systems that best account for the vein fractures, and movement along the fault is largely post-mineral. The fault evidently is the result of late structural adjustment of the gravity type, with a vertical component of movement of about 50 m.

Llallagua.—In an early study (71) of the Llallagua vein pattern, emphasis was placed upon regional stress to account for the observed relationships. Subsequently Moon (54) presented an improved analysis, in which he correlated the vein fractures with two major faults of the strike-slip type, but results were not entirely satisfactory. McKinstry (50, p. 184; 51) suggests that some of the difficulty may arise because of successive stages of fracturing, and he also points out that the pattern in vertical section has some of the characteristics of gravity control (Fig. 12). In the present analysis, which gives reasonably good results, two major episodes of fracturing are involved: regional stress at an early stage determined the framework of the pattern; gravity provided the dominant control during the later stage (Table 6).

Viewed in broad perspective, the Llallagua vein system occurs within a block bordered by two regional strike-slip faults, the Uncia and Kala Cruz, whose average strike in the mine area is N 25° W (Fig. 4). The net slip on the two faults is 995 and 2,800 m respectively. Movement on the Kala Cruz fault, which dips steeply west, was slightly inclined; movement along the Uncia fault, a warped surface dipping from 75° W to 70° E, was strictly horizontal (54). From this record it is concluded that the shear couple acted in the horizontal plane, the intermediate stress axis being about vertical.

Although principal movement during the period of regional shear took place along the two strike-slip faults of N 25° W strike, the N 55° E vein fractures, which show considerable gouge, are believed to represent the conjugate shear planes, making an angle of 80° with the two faults. Theoretically the vein fractures should be vertical, but instead they dip in either direction at about 70° (Fig. 11). From the record in other districts, however, it is concluded that fractures developed under shear are not necessarily vertical but may have a steep dip, the precise angle depending upon local conditions (6, p. 62–74; 56, p. 71–74; 10, p. 95–96).

The Contacto vein (N 72° E) probably forms a part of the N 55° E vein group, but its distinctive location and departure from the average strike of the group raise some question as to its origin. The change in strike is gradual and probably an expression of wall-rock control, but the vein may represent an early fracture or fault reactivated and extended during the period of regional shear. The Diaz and Stanton faults, which strike N 14° W and dip 82° W, give evidence of strong movement, but the lack of simple offset relations and the contrast in vein pattern on opposite sides of the fault zone point to pre-mineral as well as post-mineral movement. These faults are interpreted as minor shears about parallel to the large Uncia fault; they have similar but moderate right-lateral movement. The Diaz and Stanton faults may have originated somewhat later than the main shear breaks, and a slight shift in stress orientation would account for the difference in strike (N 25° W, N 14° W).

The early fracturing at Llallagua was closely related to the great shear faults, and it was concentrated mostly within the mass of porphyry lying between the two faults. The broad framework of the complex vein system was established, consisting of veins of N 55° E strike, the Contacto veins, and the early elements of the Diaz-Stanton fault zone. The fracture pattern of the early stage is illustrated in Figure 19A.

The second stage of deformation, essentially continuous with the first, marks the period of most intense cracking; the major vein fractures of the N 30° E group were developed at this stage, together with countless small fractures of similar trend. Although the larger veins are marked by considerable gouge, the group as a whole and particularly the many vertical fractures possess features characteristic of tension. On the basis of the previous stress orientation, the planes of tension failure should strike about N 15° E rather than N 30° E. This difference could be accounted for by a slight shift in direction of maximum compression, but there are indications that the N 30° E vein fractures developed somewhat later than the shear set (N 55° E) and under a different stress environment.

The N 30° E vein group is marked by three characteristic angles of dip: 74° W, and 90° and 72° E (Table 5). The average dip is close to vertical and the fractures might be interpreted as extension breaks produced by regional compression, the variation in dip being a matter of chance. Viewed in vertical section, however, the N 30° E vein group presents a pattern suggestive of gravity control: a conjugate set of steep fractures representing potential normal faults and numerous but less persistent vertical tension

fractures (Fig. 12). The most satisfactory explanation for the vein pattern is a combination of gravity and regional forces.

With the development of the major shear faults and early vein fractures (N 55° E), regional stress subsided and the effect of gravity increased. During the later stages, the force of gravity might exceed the forces acting in a horizontal plane; the axis of maximum stress would then shift from the horizontal to the vertical position. If the two horizontal stress axes are equal, the result would be a radial fracture pattern, but generally the axes are unequal and gravity features present a preferred orientation. During the late stage of deformation at Llallagua, when gravity was the controlling force, resistance within the horizontal plane was not equal in all directions and a system of fractures developed having a N 30° E strike. Continued

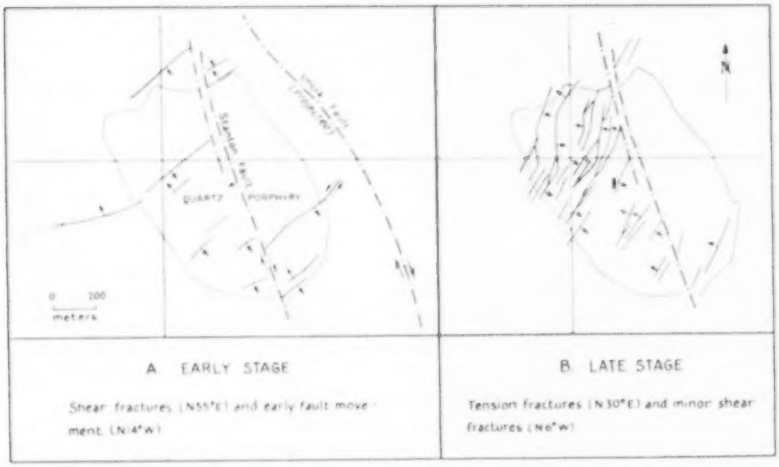


FIG. 19. Sketch showing development of the Llallagua vein pattern.

regional stress and a shift in direction of maximum horizontal pressure from N 15° E to N 30° E could account for the observed relationships. During this episode of rock failure, a few fractures striking about N 6° W were also developed. These contain considerable gouge but only scattered ore shoots; they are interpreted as minor shear breaks.

The restricted distribution of the late fractures is a noteworthy feature of the vein system. Early shear stress initiated movement along the Diaz-Stanton fault zone and the ground was divided into two distinct blocks. Subsequent fracturing was more pronounced in the westerly block, where the N 30° E vein group is prominently displayed (Fig. 19B). During this late period, adjustments also took place along the older vein fractures, and the Stanton and Diaz faults were reactivated. The late fractures combined with those of the early stage give the essential vein pattern of the district. It was

probably formed during two rather distinct episodes of deformation, each characterized by its own stress system.

Oruro.—In the description of the Oruro vein pattern, three principal and two minor vein groups were distinguished (Table 5). Four of the groups are approximately parallel to igneous trends (Table 3), and it is evident that rock distribution has been a major factor in localization of the vein fractures. The wide variation in vein attitude is evidence of complex stress conditions and raises a question as to the importance of regional stress in the development of the vein fractures. However, the early fractures that controlled dike directions seem to be the product of regional stress oriented in accordance with Andean folding (Table 4). The renewed application of stress of the same orientation would surely promote the development of new fractures parallel to the dike directions. Maximum compression would then be oriented east–west and conjugate shear planes would strike northwest and northeast. In favor of this scheme is the greater persistence of the northwest and northeast vein groups, which indeed may represent directions of shear failure (Fig. 18). The major veins, however, are not vertical but show average dips of 67° SW and 65° NW respectively. Tension fractures correlated with the conjugate shears should have a strike of N 85° W and nearly vertical dip (Table 6). Veins of the N 84° W group have the required strike, but the strongest vein of the group, the Bronce, dips 65° S. This departure from the ideal attitude may be due to local stress conditions or it may be a reflection of the southerly dip of the strong Purisima vein to which the Bronce is related.

Some change in stress orientation probably takes place during a prolonged period of deformation. A shift in direction of maximum compression to the northeast, for example, would strengthen the early northeast fractures and might create new shear fractures of northerly strike and westerly dip, such as the Nueva and Quintanilla veins (Table 6). The veins of San Luis and Colorado are rather isolated and of somewhat different character. The San Luis vein group of N 49° W strike occupies a northeast zone that follows the contact of the Itos stock (19, Fig. 26). This arrangement suggests that the stock provided a resistant core to the prevailing pressure, probably directed from the east or southeast. Thus the San Luis veins may be comparable to the northwest Purisima system or they may reflect some local modification in stress. The Carnival and Grande veins, at right angles to the assumed pressure, may correspond to potential thrust faults or may be elements of sheer, deflected from the usual course by the Itos intrusion.

In an analysis of the vein pattern, Chace (19, p. 377, 382) concludes that the vein fractures are primarily of local origin. He attributes the fractures to upthrust from below, followed by subsidence under control of gravity. Regional forces, however, may have contributed to the development of the pattern, especially in the early stages. As regional stress subsided, a general settlement of the ground probably took place, accompanied by minor differential movement and formation of new fractures, especially in the hanging-wall of major veins.

Huanuni.—Although the Huanuni vein pattern is very complex, four major vein groups can be distinguished on the basis of general trend, most of the veins having rather low dips (Table 5). The multiplicity of vein attitudes, as well as irregularity in vein distribution, precludes the development of the veins by a simple stress system but suggests instead control by local forces. Yet the pattern does possess a certain unity, expressed chiefly in the Grande vein system and its gradual change in both directions to vein structures showing a lattice arrangement (Fig. 17).

The Grande vein, the dominant element of the N 51° E group, does not show strong gouge nor significant displacement, but it is marked by wide zones of breccia, interpreted as the product of hydrothermal corrosion of badly fractured ground. The record suggests that the vein represents a "blunt" tension opening, highly permeable to circulating solutions, rather than a fault fissure of major size. Both to the northeast and southwest, the Grande vein merges with veins of easterly (N 79° E) strike, the divergence being some 30°. The lateral change may correspond to a change from northeast tension (extension) fractures to shear breaks of easterly strike, the complementary set of shear planes being correlated with veins of the N 9° E group. This stress system gives a reasonable explanation for the strike of the three vein groups but it fails to account for their variable dip.

The Grande vein, as well as the Nueva, dips southwest at an unusually low angle (40°), and the main veins of easterly strike likewise dip south but are somewhat steeper. The reason for this pronounced southerly dip is unknown; it may be connected with the complex geology of the Huanuni anticline, marked by early thrust faults and by transverse faults of the gravity type. Whatever the cause, the low dip itself does not eliminate the possibility that the two fracture sets represent combined tension and shear. But on the basis of average figures, the second set of shear planes should strike N 16° E and dip 47° E (Table 6). A few veins just east of the Grande have approximately this attitude, but the majority of veins of northerly strike dip to the west. These are presumably of independent origin, perhaps related to other fractures of easterly strike but of northerly dip such as the Oriente vein.

In the area southwest of the Grande, the N 79° E vein group is well represented, but small veins of N 41° W strike take the place of the N 9° E vein group. In the region to the north, some veins conform to the principal vein groups but others depart from the usual trends. Such variations from place to place no doubt reflect stress conditions that are equally variable.

It is evident that no simple stress system is adequate to explain the Huanuni vein system. Some of the larger veins may be due to regional stress, but many of the irregular vein groups probably owe their origin to the action of gravity, with local adjustments taking place in sedimentary formations of varied dip and contrasting strength. It may be significant that the major vein fractures attributed to tension occur in the highly silicified zone along the crest of the anticline, whereas the lattice type of pattern is best developed on the two limbs of the fold, where alternating beds of shale and sandstone prevail.

Conclusion.—The record of the vein patterns indicates that deformation following intrusive activity continued over a considerable period of time. Forces were adequate to produce complex fracture systems of high permeability but extensive faulting along the vein fractures did not occur. At Llallagua, movement along major shear faults probably initiated the development of the vein fractures, but elsewhere the connection with major regional elements is not well defined.

The Morococala vein pattern is, perhaps, the simplest, and the narrow parallel veins are interpreted as a series of tension fractures related to regional compression. The vein systems of Llallagua and Potosi seem to be the product of two or more periods of deformation during which both regional and vertical forces were active. The larger vein elements at Oruro and Huanuni are somewhat similar to those produced by regional stress, but the diversity in vein attitudes and irregularity in vein structure point to highly varied stress systems in which the force of gravity may have been dominant. Local variations in vein pattern, evident in each district, probably reflect the complex geological environment with formations of contrasting strength, a wide range in structure, and numerous irregular contacts.

The possible correlation between elements of regional structure and localization of ore districts is a highly speculative subject. Regional transverse faults are characteristic of the larger fold belts, but the degree to which these have controlled intrusive activity and mineralization is unknown. Three of the districts are situated on anticlines that are marked by belts of relatively competent formations, but two districts fail to show such a correlation. The presence of small stocks of altered quartz porphyry is a favorable sign, but two districts provide exceptions to this generalization. Doubtless many factors play a part in the localization of ore districts, but selection of the truly significant relations will remain uncertain until a large part of the Andean belt has been mapped and more is known of the tectonic setting of the ore deposits.

DESCRIPTION OF THE ORE DEPOSITS

GENERAL FEATURES

Ore-Bearing Area

The ore deposits in each district are confined to an extremely small area, ranging from 0.6 to 1.7 sq km (Table 7). At Potosi, Llallagua and Oruro the ore-bearing area is closely related in space to the main intrusive bodies, but the two do not coincide as many veins are enclosed in the older sedimentary and volcanic formations. At Morococala and Huanuni, igneous activity is represented by a few narrow dikes, and the principal veins and stockworks lie within broad areas of altered sedimentary rocks.

Structural Types

Most of the veins are not simple mineralized fissures but are of lodelike character, composed of several mineralized fractures. The veins split and

TABLE 7

AREA OF INTRUSIVES AND ORE BEARING ZONES

District	Area of intrusive				Ore-bearing zone		
	Surface		Lower levels		Length (m)	Width (m)	Area (sq km)
	Elev. (m)	Area (sq km)	Elev. (m)	Area (sq km)			
Llallagua	4400	1.25	4000	0.50	1400	1000[1]	1.40
Potosi	4700	1.25	4200	0.15+	1200	1200[2]	1.44
Oruro	3850	1.70	3600	0.20+	1400	900[2]	1.26[3]
Huanuni	—	—	—	—	1400	1200[2]	1.68
Morococala	—	—	—	Small dike	1000	600[2]	0.60[4]

[1] Average width; ore zone irregular.
[2] Maximum width.
[3] Excludes Tetilla vein group.
[4] Includes Reserva group.

coalesce within short distances; en echelon patterns and loop structures are common. Some of the Oruro veins simulate a shingle structure (19, p. 369). The main veins, as a rule, have a strike length of 300 to 700 m and generally average from 30 to 80 cm in width; some widen out to form ore shoots of phenomenal value from 2 to 3 m in width. A large amount of ore has come from rich but narrow veins from 3 to 20 cm wide. These occur as independent units, as branches of the larger veins and as links connecting other veins. Few can be traced for more than 200 m.

Wide zones of intense sheeting are found at Llallagua and Potosi. Those of Llallagua commonly occur in association with major veins; the zones range from 30 to 80 m in width and from 100 to 200 m in length. The large sheeted zone at Potosi is restricted to the silicified porphyry of the upper levels. The zone reaches a width of 175 m and a maximum length of 350 m. The zone is composed of hundreds of parallel veinlets from 1 to 5 cm in width (Figs. 13, 15).

Typical stockworks are found at Morococala, where chimney-like bodies of shattered rock, locally known as "clavos," have been productive in the past. The largest body, the Clavo Grande, forms an oval area about 100 m across and 180 m in vertical height (Fig. 16). As the productive section lies entirely within the zone of oxidation, the lower limit of ore may correspond to a change from oxide to sulfide rather than to an abrupt reduction in the degree of fracturing.

Irregular, elongated bodies of breccia, some of which are ore-bearing, are found in the Huanuni district. The fragments are composed of sandstone and silicified shale; the abundant matrix is composed of iron oxide, clay and a variable amount of cassiterite. Many breccia bodies of veinlike form are not over 30 cm wide and 20 m long, but these may grade into large, irregular bodies up to 30 m in width. Some of the breccia lenses terminate against cross fractures; others have tongue-like projections that resemble

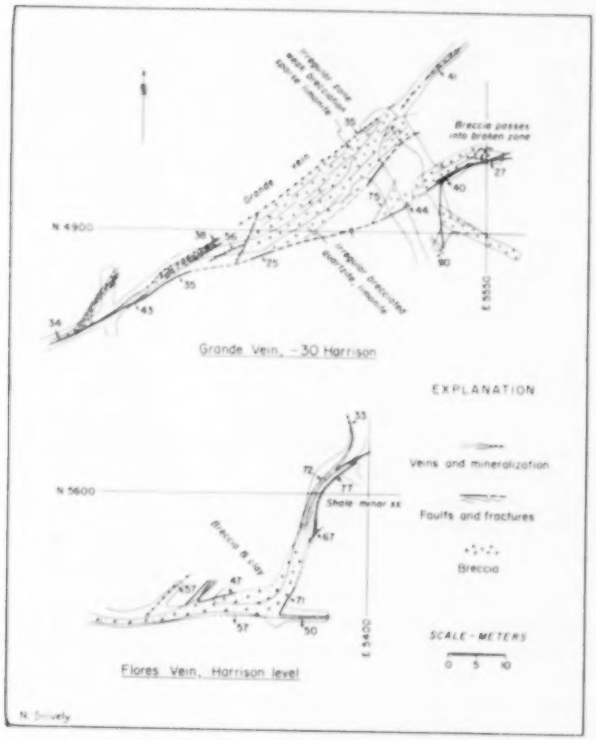


FIG. 20. Details of breccia zones. Huanuni mine.

branching veins (Fig. 20). The distribution of the breccia precludes a simple tectonic origin.

Ore-bearing breccias have also been mined at Llallagua, the principal bodies occurring near the southeast margin of the intrusion where the border is extremely irregular (21, p. 173). In the typical breccia, most of the fragments are composed of silicified graywacke, and the ore minerals occur chiefly in the fine matrix.

WALL-ROCK ALTERATION

Most of the igneous rocks of the mining districts have been altered to such a degree that their original nature is difficult to determine. Thin-section studies suggest that the porphyry of Llallagua and Oruro is best classified as quartz latite and that of Potosi as quartz latite or dacite. The sedimentary rocks that surround the stocks have been altered to a moderate degree, whereas the sedimentary rocks of the productive zones at Morococala and Huanuni are intensely altered (Table 8).

TABLE 8

WALL-ROCK ALTERATION

District	Principal wall rock	Alteration minerals													
		Chlorite	Sericite	Tourmaline	Quartz	Cassiterite	Pyrite	Topaz	Rutile	Hematite	Kaolinite	Dickite	Alunite	Calcite	Serpentine	Fluorite
Llallagua	Quartz latite	x	●	●	○	x	x		x							
Potosí																
Upper levels	Dacite or quartz		x		●		○									
Lower levels	latite	○	●	?	○		x						x		x	
Oruro	Quartz latite	○	●	x	○		○			x	x	x	x	x		
Morococala	Graywacke		x	●	●	○	x	x								
Huanuni	Sandstone, shale		x	○	●	x	x									x

● = Abundant; ○ = Common; x = Minor.

The characteristic minerals of the altered porphyry are chlorite, sericite, quartz, tourmaline, kaolinite and alunite. Pyrite is abundant at Oruro. Sericite, quartz and tourmaline are predominant in the altered sedimentary rocks. A little topaz has been found at Morococala and fluorite at Huanuni.

Description of the Altered Rocks

Llallagua.—Sericite, the most common metasomatic product at Llallagua (71), replaces phenocrysts of the porphyry and is abundant in the groundmass as well. Tourmaline, characteristic of the highly altered porphyry, forms pseudomorphs after biotite and occurs with sericite in the replacement of feldspar. Tourmaline is also abundant in the clastic dikes, intrusive breccias and bands of black porphyry. These highly tourmalinized rocks are structurally independent of the veins and are not themselves ore bearing.

Quartz is a common mineral of the altered rocks. In some specimens the groundmass of the porphyry is replaced by a fine quartz mosaic, whereas the feldspar phenocrysts are replaced by sericite. Highly silicified porphyry is most commonly found along the veins, and the fine quartz mosaic may merge with the coarse quartz of the veins.

Cassiterite occurs in scattered grains but is not sufficiently abundant to form disseminated ore. It is more closely associated with tourmaline than with sericite. Rutile and pyrite are minor alteration products. Chlorite, associated with sericite, occurs in some of the marginal porphyry dikes.

The graywacke has been altered but to a less degree than the porphyry. Shreds of coarse sericite are common, tourmaline is abundant in places, and quartz invades the fine matrix. The ore-bearing breccia constitutes a special rock type. The fragments, consisting of altered graywacke, are composed of fine-grained quartz with some tourmaline; the cassiterite occurs chiefly in the matrix, associated with tourmaline. Whether intense silicification preceded or followed brecciation cannot be determined from the mineral textures.

Potosi.—The lower part of the Potosi stock is made up largely of highly sericitized porphyry. According to Lindgren and Creveling (45), phenocrysts of feldspar and mica have been replaced by sericite and quartz, and the same alteration products appear in the groundmass, together with a little alunite. Tourmaline may be present as minute needles but it has not been positively identified. Less altered porphyry in which the biotite and feldspar phenocrysts are replaced by chlorite has been described by Jaskolski (34, p. 54).

The most remarkable feature of alteration at Potosi is the intense silicification that has affected the upper portion of the stock. The groundmass of the porphyry is composed of a fine quartz aggregate; the feldspar phenocrysts are represented by angular cavities or by patches of claylike material. Embayed quartz phenocrysts can be recognized. Chemical analyses show 95.65 percent silica in the intensely altered type (34). Below the Caracoles level, the silicified porphyry passes downward into the sericitized type, but the transition zone has not been studied in detail.

Oruro.—The altered rocks of Oruro have been well described by Chace (19, p. 435–439), who distinguishes three gradational types. These may be summarized as follows:

(1) Feeble phase. Plagioclase phenocrysts are partly altered to sericite, chlorite and calcite. The biotite is converted to chlorite and hematite. This type of alteration is widespread.

(2) Moderate phase. Many plagioclase phenocrysts are completely destroyed and replaced by sericite. Pyrite is abundant and a little quartz is present. The San Jose and Itos stocks are altered in this manner "throughout their entire extent" (p. 436).

(3) Intense phase. The phenocrysts have lost their identity and the rock is composed of masses of quartz, sericite, kaolin and pyrite. Some alunite and dickite are present and possibly tourmaline. Intense alteration is restricted to the vein borders.

Alteration of the San Jose breccia is usually more severe than that of the porphyry mass as a whole. The porphyry fragments are thoroughly sericitized, and the clastic matrix is altered to sericite and quartz. Pyrite is abundant.

Morococala.—Intense alteration of the graywacke at Morococala has produced two oval areas, the largest of which measures 600 by 200 m (Fig. 16). Most of the productive veins and stockworks occur within the areas of alteration. The altered graywacke is a dense, brittle rock, composed of secondary quartz, abundant tourmaline and variable amounts of cassiterite. The progressive nature of the alteration has been described by Hosmer (33). Initial attack produced widespread silicification and recrystallization of sericite. Tourmaline and cassiterite were then deposited, both as a metasomatic product and as a filling of small solution cavities. Most of the cassiterite followed tourmaline, selectively replacing the earlier quartz. The "silicified" graywacke generally shows abundant tourmaline, but some specimens give

little evidence of tourmaline deposition preceding that of cassiterite. The cassiterite of the veins, many of which are sharply defined, is also of replacement origin, its deposition being controlled by small fractures. A little topaz has been observed in the altered graywacke.

Huanuni.—The country rock at Huanuni consists of sandstone with a minor quantity of shale. The sandstone has been converted to dense quartzite and the shale beds have also been silicified. Some of the quartzite may represent an original sedimentary quartzite, and the altered zones are not sharply defined. Underground mapping by Snively shows that silicification is most pronounced in a wide belt of sandstone that occupies the axial zone of the Huanuni anticline; it is less conspicuous on the limbs of the fold where the country rock consists of alternating sandstone and shale. The most intense phase of silicification seems to be localized in part along the vein fractures. Tourmaline in small amount may be widely distributed, but as an important constituent it is largely restricted to the vein walls. A little disseminated cassiterite was noted in thin section. Fluorite occurs as an accessory vein mineral but is rarely found in the altered wall rock.

(*To be continued in next number*)

Economic Geology
Vol. 55, 1960, pp. 255–277

GENESIS OF THE GORE MOUNTAIN GARNET DEPOSIT, NEW YORK

P. BARTHOLOMÉ

CONTENTS

	PAGE
Abstract	255
Introduction	255
The Adirondack garnet deposits	258
The rims of the garnet porphyroblasts	261
Porphyroblasts versus coronas	265
The age of garnet	267
Mineralogical and chemical composition of the dark ore	268
Nature of the metamorphism	271
Metamorphic differentiation in the dark ore	272
Conclusion	276
Acknowledgments	276
References	277

ABSTRACT

In the south-central Adirondacks, garnet porphyroblasts are found in rocks of various compositions and origins. However, they are abundant only in basic rocks. Their shape, habit, size, and composition depend on the nature of the host rock. They are commonly surrounded by rims or shells whose composition also depends on the nature of the host rock. On the other hand, garnet porphyroblasts are not found in basic rocks that have kept relics of their magmatic texture and mineralogy. Such rocks contain garnet only as coronas. These observations show that garnet porphyroblasts have grown in situ after a period of intense componental movements.

The available chemical data suggest that the formation of the Barton Mines dark ore results from a process of metamorphic differentiation taking place during a period of rising temperature. There is no reason to suppose that metasomatic changes have been important.

INTRODUCTION

THE Gore Mountain area is well known for its garnet deposits, the most important of which has been mined for several decades by the Barton Mines Corporation. It is situated in the Adirondack Mountains of New York State (Fig. 1), south of the central region where anorthosite and anorthositic gneiss prevail. The reader is referred to Buddington (7, 8) for the general geology and petrology of the Adirondack Mountains, and to Balk (2), Krieger (14), and this writer (5) for local problems.

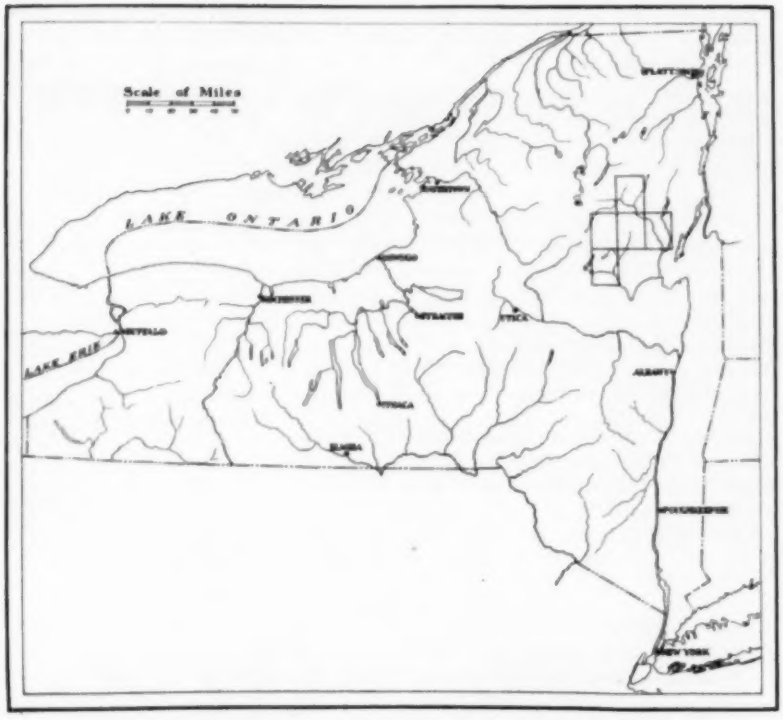


FIG. 1. Index map. Location of the area shown in Figure 2.

The south-central Adirondacks are essentially made of three structural elements: a) an irregular dome of anorthosite whose upper surface shows minor domes separated by deep synclines; b) a mantle of syenite gneiss a few thousand feet thick that covers the anorthosite dome, and which contains conformable lenses and layers of anorthosite and gabbroic anorthosite gneiss; c) a metasedimentary sequence (marble, quartzite, amphibolite, and various types of gneiss), which overlies the syenite mantle and contains sheets of olivine gabbro and of syenite gneiss. The Gore Mountain area is within the syenite mantle on the north-eastern side of the anorthosite dome. Several lenses of gabbroic anorthosite gneiss, some of them quite rich in pophyroblastic garnet, crop out in the neighborhood. A belt of metasediments is observed a few miles to the north-east.

A most important feature of the geology throughout the Adirondacks is the conformity of sedimentary, magmatic, and metamorphic structures (7). As a rule, intrusive bodies are sheets and domes so that their contacts are parallel with each other and with stratification in the metasedimentary wall-rock. Furthermore, gneissic structures (foliation and lineation) are always

found to be parallel with primary structures (contacts, bedding planes, magmatic layering). It follows that the patterns obtained by plotting the strike of the foliation and of the lineation on the map are made of smooth, continuous, parallel curves; they are similar to flow patterns.

As compared with the whole of the south-central Adirondacks, the area around Barton Mines is anomalous in three respects. First, the thick lens of gabbroic anorthosite gneiss that crops out north of the mine is intruded by an elongated stock or a thick dike of olivine gabbro; this intrusive body has nearly vertical contacts and thus does not conform to the regional structure. Second, the gneissic structures of the syenite gneiss in the vicinity follow directions that do not fit into the regional pattern. Thirdly, unusual rock types are found in the contact zone between syenite gneiss and olivine gabbro. Among these are the *dark ore*, the *light ore* and a non-gneissic hornblendite. The dark ore is a porphyroblastic garnet amphibolite made of almost spherical crystals of red garnet (up to 30 cm in diameter) surrounded by a shell of black shiny hornblende and embedded in a medium-grained matrix made of hornblende and plagioclase with minor orthopyroxene. The light ore is a non-gneissic porphyroblastic garnet anorthosite. These rocks, as well as others, have been described earlier in more detail by Levin (16) and by this writer (5).

The garnet deposits of the Gore Mountain area, especially the largest one being mined by the Barton Mines Corporation, have been investigated by several workers. Miller (17, 18, 19) became interested in them in the course of his field work in the south-central Adirondacks, of which he mapped several quadrangles. Later R. Balk (1, 2) mapped a large area north of Gore Mountain as a part of a study of the anorthosite problem and he described briefly some of the smaller garnet deposits. His methods, including the systematic surveying of lineation, foliation, joints, and of all the structural features of the rocks, proved to be so successful that they were followed by all later investigators. Among these, M. H. Krieger deserves special mention; she contributed the geological map of the 15′ quadrangle (Thirteenth Lake) containing the most important garnet deposits (14); she also wrote a comprehensive discussion of the origin of garnet ores. Krieger's work was followed by several petrogenetic studies, which include Shand's (21) contribution on the origin of coronites, Shaub's (22) paper on certain particular textures of the garnet ore, Levin's (16) extensive work on the mineralogy of the ore and Buddington's discussion of garnet as a regional product of dynamothermal metamorphism (9). Finally, mention should be made of Wentorf's (26) experimental approach to the problem.

Various hypotheses have been proposed to explain the origin of the Adirondack garnet deposits—magmatic crystallization, contact metamorphism, hybridization, regional metamorphism of a metasediment or of metagabbro.[1]

Levin's work, however, left no doubt that the garnet ore was for the most part a metamorphosed olivine gabbro so that the disagreement narrowed down to two main problems, namely, 1, the nature of the metamorphism, whether

[1] The reader is referred to Levin, p. 553–561 for a discussion of these hypotheses.

thermal or dynamothermal; and 2, the age of the deposit whether pre- or syn-orogenic.

Levin advocated a rather complex hypothesis of origin that may be summarized as follows: a) garnet coronas in the olivine gabbro are a product of deuteric activity; b) garnet porphyroblasts have developed mainly by recrystallization of corona garnet; this recrystallization was induced by the intrusion of syenite magma; the Barton Mines dark ore was formed in that manner; c) some of the porphyroblastic rock just formed was assimilated by the same syenite magma; in the process, hornblende and garnet crystals were caught up as xenoliths; this is the origin of the Barton Mines light ore. Thus, according to Levin, garnet ores are entirely pre-orogenic. Levin's hypothesis was criticized by Buddington (9) on the following grounds: a) the occurrence of garnet in the Adirondacks is related to the grade of regional metamorphism; b) in areas where the regional metamorphism is intense enough, coronitic and porphyroblastic garnet have grown in the syenite gneiss as well as in basic rocks; c) the composition of garnet porphyroblasts varies with the nature of the host-rock; which seems to imply that porphyroblasts, especially those of the light ore, are not xenoliths.

The present writer will attempt to review the problem in the light of additional data that are believed to be critical. Some new observations on the structure and the petrography have been published in a previous paper (5) as well as a detailed map of the deposit. They will be summarized only very briefly here.

THE ADIRONDACK GARNET DEPOSITS

Garnet is a very common mineral in the Adirondacks; it is found in gneisses of granitic, syenitic, gabbroic and anorthositic composition as well as in non-gneissic rocks such as coronites. However, rocks where garnet is abundant enough and coarse-grained enough to warrant mining have been found only in a rather small area in the South-Central Adirondacks (Figs. 1, 2). On the basis of field and lithological evidence, these garnet ores can be classified into four types:

Dark Ore.—This has been observed (and mined) at the following localities: 1) Barton Mines, just north of Gore Mountain, in the Thirteenth Lake quadrangle. It has been shown earlier that, to the north, the dark ore grades into granoblastic norite gneiss and then into olivine gabbro; to the south into hornblendite (5). 2) One mile east of McGinn Hill, Newcomb quadrangle. This deposit, which is mentioned by Balk (2, p. 86), lies within a body of corona-bearing olivine gabbro; no outcrop of syenite gneiss has been found in the neighborhood by this writer. The dark ore forms an elongated mass that grades on *both sides* into granoblastic norite gneiss and then into olivine gabbro. 3) Near the top of Humphrey Mountain. This deposit, which has been described by Krieger (14, p. 115), lies within a body of olivine-gabbro, and not at the gabbro-syenite contact as Krieger states; in fact along this contact, which is several hundred yards farther east, the gabbro is transformed into a dark medium-grained gneissic amphibolite that contains garnet as an *occasional constituent only*. 4) Near Bullhead pond, Newcomb quad-

rangle. This deposit, which is mentioned by Balk (2, p. 85), lies south of an olivine-gabbro body into which it grades. The southern contact is concealed under old tailings and recent sediments.

In all these localities, the dark ore presents the same features: the garnets are spherical, large (usually 2″ to 4″ in diameter, much larger in Barton Mine), surrounded by a thick rim of hornblende; the matrix made of plagioclase and hornblende is homogeneous and massive except for a few scattered plagioclase pegmatites. The dark ore is associated with olivine-gabbro. The association with syenite gneiss observed at Barton Mines is accidental.

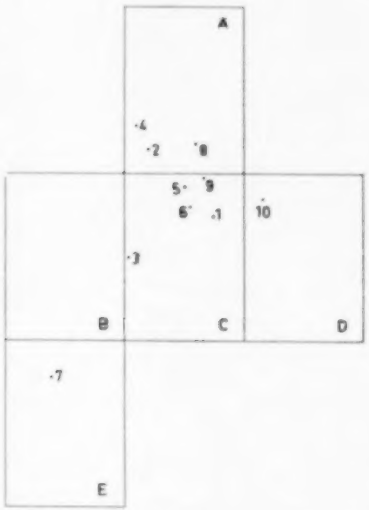


FIG. 2. Location of Adirondack garnet deposits. 1—Gore Mountain, 2—McGinn Hill, 3—Humphrey Mountain, 4—Bullhead Pond, 5—Ruby Mountain, 6—Hooper Mine, 7—Lake Pleasant, 8—Crehore, 9—Old Hooper Mine, 10—Rexford and Owen Mountain. The 15′ quadrangles referred to in this paper are the following: A—Newcomb quadrangle, B—Indian Lake quadrangle, C—Thirteenth Lake quadrangle, D—North Creek quadrangle, E—Lake Pleasant quadrangle.

Porphyroblastic Gabbroic Anorthosite Gneiss.—This has been observed at the following localities: Ruby Mountain, Thirteenth Lake quadrangle and Hooper Mine, Thirteenth Lake quadrangle.

Other occurrences and isolated outcrops are known north of Gore Mountain where they form the so-called Hooper vein (14, p. 102–103), as well as in the Lake Pleasant quadrangle. As mentioned above, the lenses and layers of gabbroic-anorthosite gneiss included within the syenite mantle commonly contain abundant garnet porphyroblasts. This type of garnet ore, which is in fact the most common, is strikingly different from the dark ore: the garnets

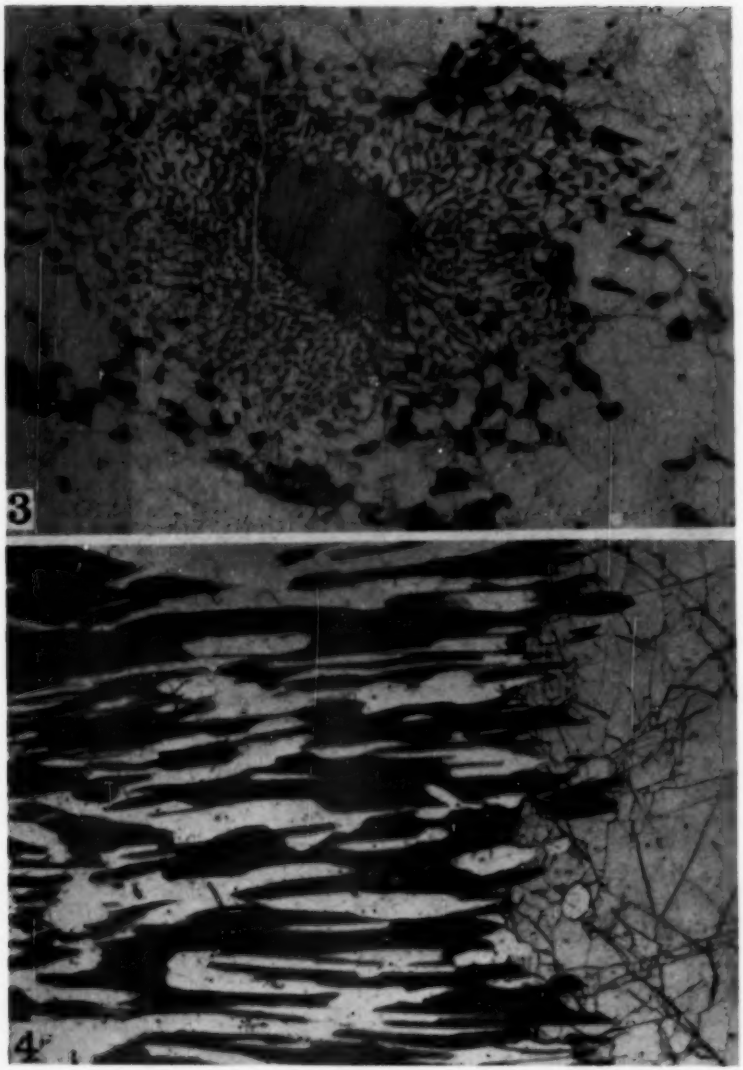


FIG. 3. Garnet porphyroblast in anorthositic gabbro gneiss from Lake Pleasant (× 13). Plane light. This porphyroblast is surrounded by a dactylic intergrowth of hypersthene and hornblende stringers in plagioclase. The matrix of the rock is plagioclase (andesine-labradorite) with hornblende, clino- and orthopyroxene with minor magnetite and ilmenite, and a trifle of apatite.

FIG. 4. Kelyphite pseudomorph after garnet from the Gore Mountain dark ore (× 7). Plane light. The kelyphite, which is made of a plagioclase-biotite

are small (mostly less than 2 inches across); they are embedded in a medium-grained, strongly gneissic matrix of gabbroic anorthositic composition consisting of andesine-labradorite with minor hornblende, clino- and orthopyroxene, magnetite and ilmenite. In the more feldspar-rich varieties as at the Hooper mine, the garnets are euhedral and do not have any rims. In the more mafic varieties, they are surrounded by dactylic intergrowths of hypersthene and/or hornblende with plagioclase (Fig. 3). Similar intergrowths have been interpreted by Subramanian (23, p. 364–365) as keliphitic intergrowths due to a diaphtoretic replacement of garnet. As shown later, this writer has reached a different conclusion. In Barton Mines, keliphitic intergrowths are also found (Fig. 4); they are mineralogically and texturally different from those described here; moreover they are found only where a garnet is adjacent to a plagioclase pegmatite (5, p. 19).

Porphyroblastic Garnetiferous Amphibolites of the Metasedimentary Sequence.—The metasedimentary belt north and north-east of Gore Mountain includes lenses and layers of garnetiferous amphibolites especially at the following localities: Crehore deposit, Newcomb quadrangle (2, p. 86), Old Hooper deposit, Thirteenth Lake quadrangle (14), Rexford and Owen Mountain deposits, North Creek quadrangle (18).

These rocks have not been studied in detail. Quite possibly, some of them should be classified with the dark ore. Most of them however differ from the dark ore by the gneissic and heterogeneous structure of the matrix, as well as by the irregular shape and occurrence of their garnets. They are interlayered with marble and quartzite, sometimes on a small scale, which suggests a metasedimentary origin for the host rock.

Light Ore.—To the writer's knowledge, the only occurrence of this rock is at Barton Mines. Compared with porphyroblastic gabbroic anorthosite gneiss, the light ore is remarkable by its non-gneissic matrix and by the rims of pure plagioclase that surrounds the garnets.

Thus garnet ores are in all cases basic rocks where garnet is associated with pyroxenes, hornblende, and an intermediate plagioclase. It should not be concluded however that large garnet porphyroblasts are not found in other rocks. They do occur although rarely in syenite gneiss (Fig. 7), and more commonly in quartz-bearing gneisses. In short, their occurrence is by no means restricted to gabbro-syenite and anorthosite-syenite contacts. Since on the other hand such contacts are commonly devoid of garnet, it cannot be asserted that the intrusion of syenite magma has played a major role in the genesis of garnet ores.

THE RIMS OF THE GARNET PORPHYROBLASTS

Garnet porphyroblasts in the Adirondack basic rocks are commonly surrounded by rims or shells of various sorts. Some of these rims cannot be seen with the unaided eye. Others, such as the hornblende shells in the dark ore, are most conspicuous.

---

symplectite, is found where the garnet is in contact with plagioclase pegmatites. The volume of the kelyphitic intergrowth is not related in any way to the volume of the garnet.

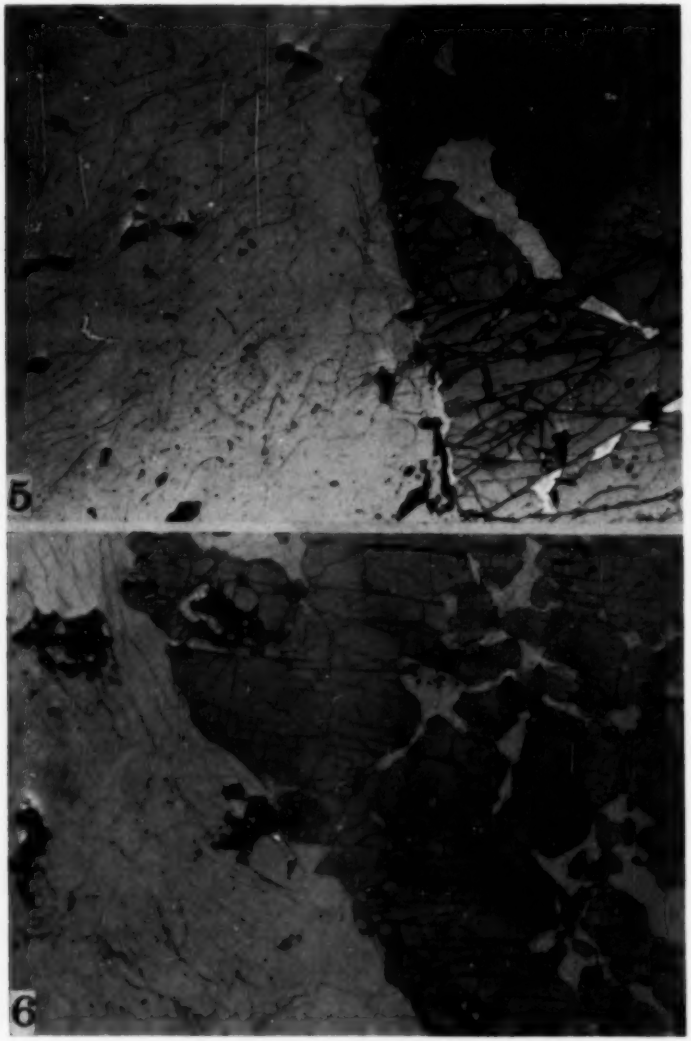


FIG. 5. Idiomorphic garnet pophyroblast in the Gore Mountain light ore (× 10). Plane light. The garnets are idiomorphic and 20 to 30 mm across. They do not contain any inclusion except of ilmenite and apatite (the white areas within the garnet are holes). The matrix of the rock is basic andesine with minor hornblende; biotite and ilmenite are accessory; there is a trifle of apatite. In a 10 mm-wide rim around the garnets, the matrix is devoid of hornblende as shown on the photograph. Ilmenite is about as abundant in the rim or in the

TABLE 1

MINERALOGY OF RIMS AROUND GARNET PORPHYROBLASTS

Composition of the rock	Mineralogy of the matrix	Rim	Example
Olivine-gabbro	Hornblende, plagioclase, minor orthopyroxene	Massive hornblende	Barton Mines dark ore
Anorhositic gabbro	Plagioclase, orthopyroxene, clinopyroxene, hornblende	Dactylic intergrowth of plagioclase with hornblende and/or hypersthene	Lake Pleasant anorthositic gabbro gneiss
Anorthosite or gabbroic anorthosite	Plagioclase with minor pyroxene and/or hornblende	Massive plagioclase	Barton Mines light ore

This writer's observations on the rims lead to the following generalizations:

1), The mineralogy of the rim depends exclusively on the bulk chemical composition of the rock; the relationships are summarized in Table 1.

2), In a given rock, for instance in the dark ore, the volume of the rim increases with the volume of the enclosed garnet. Observations on a sufficiently large number of samples show that this rule holds true although exceptions may be found locally.

Other generalizations relevant to the problem of the origin of garnet are:

3), As observed by Buddington, the chemical composition of the garnet depends on the nature of the host-rock.

4), The shape of a porphyroblast depends essentially on the minerals that form the rim. Garnets surrounded by plagioclase grains, such as those of the Barton Mines light ore and those of the Thirteenth Lake deposit, are commonly idiomorphic (Fig. 5). On the other hand, where the rim contains appreciable amounts of hornblende or pyroxene, garnets are round. In syenite gneiss, porphyroblasts are also round (Fig. 7).

5), The number, size, and nature of inclusions in garnet porphyroblasts depend on the nature of the host rock. Thus, garnet from the dark ore contain few large inclusions; garnets from the hornblendite may be poikilitic or skeletal; garnets from the light ore may contain numerous small inclusions (Fig. 6) of characteristic shape and composition.

In the writer's opinion, these observations prove conclusively two things:

1), *The garnet porphyroblasts have grown in the environment where they are now found;* they cannot be xenoliths. In particular, the light ore garnets

garnet as in the matrix. This shows that ilmenite did not participate in the garnet-forming reaction.

FIG. 6. Poikilitic garnet porphyroblast in the Gore Mountain light ore (×7). Plane light. In addition to the idiomorphic garnet of Figure 5, the light ore also contains non-idiomorphic porphyroblasts that are poikilitic. The inclusions are made of zoned plagioclase displaying the same optical orientation over important areas. In the plagioclase, there are small rounded zircons.

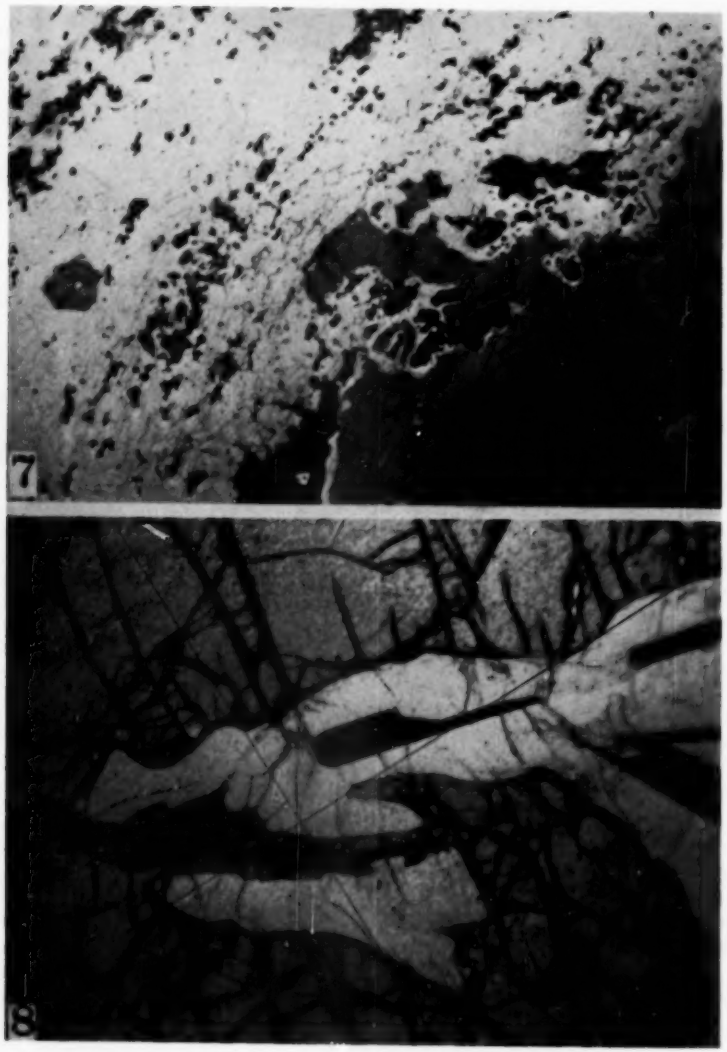


FIG. 7. Garnet porphyroblast in syenite gneiss from Lake Pleasant (× 10). Plane light. This porphyroblast is about 50 mm across and contains few inclusions. In hand specimen, it looks spherical. In thin section, the border appears to be very irregular. The matrix of the rock is made of microperthite with minor plagioclase, hornblende and quartz. The iron ores are mostly magnetite with much lamellar intergrowth of ilmenite, except close to the garnet where ilmenite and magnetite occurs as separate grains.

cannot be xenoliths as suggested by Levin, because they are commonly idiomorphic and not spherical like those in the dark ore, because of their inclusions, and because of their rim of pure plagioclase.

2), *The rim and the enclosed garnet have grown simultaneously*, the garnet developing at the expense of the rim and the rim at the expense of the matrix. Therefore, the rim does not result from a reaction between garnet and matrix; it results from the very reaction that produces garnet. Plagioclase and pyroxene (or hornblende) are among the minerals that react to yield garnet. In anorthositic rocks, plagioclase is in excess of the amount required by the reaction and this excess appears as a plagioclase rim. In gabbroic rocks, the excess of ferro-magnesian silicates appears as a hornblende rim. In gabbroic anorthositic rocks where garnets are particularly rich in calcium, the rim contains plagioclase and hornblende but no clinopyroxene although this mineral is present in the matrix.

From textural observations, Shaub (22) has reached the conclusion that garnet has crystallized for the most part after plagioclase, hornblende and hypesthene, in other words later than the matrix. In the writer's experience, such observations are never conclusive and may often be interpreted in several ways (Fig. 8). They cannot therefore be the basis of a petrogenetic theory.

PORPHYROBLASTS VERSUS CORONAS

In the Adirondack basic rocks, garnet may be coronitic as well as porphyroblastic. The texture displayed in a given rock is not a matter of garnet content; for coronites may be as rich as, or even richer in garnet than porphyroblastic rocks. Indeed, according to Levin, the Gore Mountain coronite may contain up to 26 percent of garnet in volume. Neither is the texture of a given rock a matter of bulk chemical composition; any basic rock can be found with either texture.

In this paragraph, the main differences between corona-bearing and porphyroblast-bearing rocks will be discussed and their significance analyzed.

1) *Coronas are found exclusively in rocks that have kept an ophitic or similar texture. Porphyroblasts are found mostly in gneissic rocks.* It is clear that the ophitic texture is magmatic in origin. On the other hand, the writer has shown (4, 5) that ophitic rocks can become gneissic by plastic flow, i.e., by deformation in the solid state but without large-scale fractures. Therefore, garnet forms coronas only in rocks that have suffered no or little deformation; in much deformed rocks, garnet forms porphyroblasts. This

FIG. 8. Biotite rimmed by garnet (×60). Plane light. This shows the border of a large garnet porphyroblast of Barton Mines dark ore. These are surrounded by a thick shell of black hornblende, with a thin inner rim of plagioclase between the shell and the garnet. This rim, of constant thickness (0.5 mm), regardless of the size of the garnet, contains a few small flakes of biotite. The plagioclase of the inner rim fills an embayment in the garnet. A biotite flake contained in this embayment is partly surrounded by narrow tongues that spring from the same garnet. This parodoxical texture, where garnet and biotite are rimming each other, illustrates the uncertainty of conclusions based on textures.

conclusion is confirmed by the tectonic control of the location and shape of the Barton Mines ore body (5).

With regard to their non-gneissic matrix, the dark ore and the light ore are exceptions among porphyroblastic rocks. As will be shown later, garnet growth takes place for the most part after gneissic structures have developed. When garnets grow large enough, gneissic structures are obliterated and a massive rock results.

2) The mineralogies of coronites and porphyroblastic rocks are compared in Table 2. Admittedly, not all the characters mentioned there can be safely interpreted; petrologists do not agree on the significance of clouded plagioclase, schiller inclusions, or pleochroic hypersthene. But some other characters give more definite evidence; the systematic absence of exsolutions in

TABLE 2

Coronites	Porphyroblastic rocks
Plagioclase	
Mostly clouded and twinned (Carlsbad, Albite and Pericline laws)	Clear and commonly untwinned (Albite and Pericline laws but no Carlsbad)
Lath-shaped	Equant grains
Pyroxenes	
Mostly with Schiller inclusions and Many (010) lamellae	Clear Lamellae are few, even in coexisting ortho and clinopyroxenes
Almost colorless	Orthopyroxene is pleochroic (pink and green). Clinopyroxene is green
Insterstitial	Equant grains
Iron Ores	
Ilmenite with hematite exsolutions	Magnetite and ilmenite
Interstitial	Equant grains
Olivine	
Present in rocks undersaturated in silica	Not present
Hornblende	
Occurs as rims and coronas	Equant grains
Garnet	
Occurs as rims and coronas	Porphyroblasts

the iron ores and in the pyroxenes of the porphyroblastic rocks indicate a *temperature of crystallization well below the melting temperatures of basic rocks* (10, 13). Similarly, the absence of Carlsbad twinning and the abundance of untwinned plagioclase grains indicate a metamorphic origin (11, 24). On the other hand, the abundance of exsolution lamellae in the pyroxenes and iron ores of the coronites indicate that these minerals have crystallized at high temperature. The ophitic texture shows that, in fact, they have crystallized from a magma.

Thus, essentially, coronites are rocks that have kept relics of magmatic mineralogy and texture. Porphyroblastic rocks are rocks whose magmatic texture has been destroyed by plastic flow, and whose magmatic minerals have recrystallized and reacted into secondary minerals. These secondary min-

erals are: clear and commonly untwinned andesine-labradorite, pleochroic hypersthene, green diopsidic augite, dark-green hornblende and pink garnet. The reader familiar with the literature on charnockites will notice that these minerals are those of the basic members of the charnockite suite. Such rocks have been found throughout the world; petrographic descriptions show that they are amazingly similar even in the details of their texture and mineralogy.

The secondary minerals that are the major constituents of porphyroblastic rocks occur also, but as minor constituents, in coronites. Thus in the Gore Mountain coronite, minute hornblende grains may occur as rims around plagioclase; pleochroic hypersthene and untwinned plagioclase are associated with garnet in the coronas surrounding olivine grains. This shows that, in coronites, magmatic minerals have also in part reacted and recrystallized, and in the same way as in the porphyroblastic rocks. However, reactions and recrystallizations were not brought to completion as shown by the persistence of relics (in particular of olivine relics).

Thus, plastic flow, by destroying the ophitic texture and by constantly bringing mineral grains in contact with each other, is a prerequisite to the complete mineralogical transformation of the rock.

THE AGE OF GARNET

Several observations indicate that garnet porphyroblasts have grown, for the most part, after plastic flow has ceased: first, inclusions are arranged concentrically or in an haphazard manner; helicitic textures are not observed; second, dactylic intergrowths are radially arranged (Fig. 3); third, foliation and lineation are generally obliterated by the porphyroblasts; they do not wrap around them.

Now, what is the age of the plastic flow and of the gneissic structures that result from it? Balk thought that the gneissic structures developed in and around an intrusive body at the time of the intrusion. But his view was not confirmed by later work; in 1939, Buddington proved conclusively that they originated during a period of orogenic folding and regional metamorphism. Buddington's evidence cannot be summarized here even briefly. Only two points will be emphasized because of their importance with regard to the Gore Mountain area: a) The *directions* of foliation and lineation at any one place are independent of rock type; they are determined altogether by the tectonic setting. Thus, in the south-central Adirondacks, lineation is parallel with fold axes. b) The *relative intensities* of foliation and lineation at any one place also depend exclusively on the tectonic setting. Thus in the nose of an anticline, gneisses display an excellent lineation but no or little foliation (4); in the limb of a fold, the reverse relation is observed whatever is the nature of the rock.

Thus we reach the conclusion that garnet porphyroblasts have grown after a period of intense componental movements. This is confirmed by Buddington's observation that garnet is found in all the prekinematic intrusives (including the rocks belonging to the syenite series), and not in the "younger granites," which are late synkinematic in age.

Levin's hypothesis requires that coronitic garnet forms earlier than porphyroblastic garnet.

I do not know of any observation that proves or even suggests such a relationship. As shown above, coronas and porphyroblasts seem to result from similar reactions; there is no a priori reason to suppose that they did not grow at the same time. On the other hand, it is obviously difficult to prove that they did grow at the same time. Only indirect evidence is available.

Garnet coronas seem to have been first observed by Lacroix (15) in basic rocks from Odgarden, Norway. Since then, they have received much attention from petrologists so that nowadays the literature contains a few papers especially devoted to garnet coronas and innumerable observations scattered through a large number of papers mostly devoted to regional geology.

From the part of this literature available to me, the conclusions clearly emerge that, 1), garnet-bearing coronites are found only in highly metamorphosed terranes, 2), these terranes also contain porphyroblastic garnet rocks.

This argument and those developed by Shand and by Murthy (20) seem to rule out the possibility of a deuteric origin for corona garnet.[2]

MINERALOGICAL AND CHEMICAL COMPOSITION OF THE DARK ORE

The minerals of the Barton Mine dark ore are rather well known. The plagioclase of the matrix was analyzed by Shand (Table 3); the optical properties are those of a low-temperature andesine-labradorite. The orthopyroxene contains 70 percent of enstatite according to Hess' curve (12). Levin analyzed a number of garnet porphyroblasts and found that they have a rather narrow range of composition: 37 to 43 percent of pyrope, 40 to 49 percent of almandite, about 1 percent of spessartite, and 13 to 16 percent of grossularite (including minor andradite). He also found that a 19-inch garnet crystal was zoned with the border more pyropic and the center more almanditic. The hornblende that forms the rim of the porphyroblasts was also analyzed by Levin. An analysis of the hornblende that forms the matrix has been made recently by Oslund and is presented here. These hornblendes are both pargasites, but their compositions are somewhat different; the matrix hornblende is significantly richer in alumina, poorer in silica and in magnesia than the rim hornblende.

In Table 4, two new rock analyses are presented. The first of these (column A) was made on a large specimen of dark ore reduced by quartering; the second (column C) on a grab-sample of hornblendite. Column A' shows the chemical composition of the dark ore as computed by Levin from the mode and from the chemical compositions of the mineral constituents. The discrepancies between A and A' are due in part to the fact that the differences between rim and matrix hornblendes were unknown to Levin. Column B gives Shand's analysis of the Gore Mountain coronite.

[2] It is often said that Brogger (6) has proven the deuteric origin of corona garnet. In fact, Brogger's paper is a careful and admirably detailed description of coronas; but his observations may be interpreted in different manners.

TABLE 3

MINERALS OF THE BARTON MINES DARK ORE. CHEMICAL ANALYSES

	1	2	3
SiO_2	55.24	41.81	43.50
TiO_2	—	1.08	1.12
Al_2O_3	28.17	15.15	13.15
Fe_2O_3	0.65	3.77	3.39
FeO	—	9.73	9.38
MnO	—	0.15	0.09
MgO	0.20	13.02	14.25
CaO	9.75	10.12	10.58
Na_2O	5.86	2.68	2.53
K_2O	0.09	0.61	0.68
H_2O +	0.17	1.56	1.15
H_2O −	—	0.03	0.12
F		0.07	0.30
Cl		0.02	—
Total	100.13	99.80	100.24
− 0 for F		−0.03	−0.12
		99.77	100.12

1. Plagioclase, dark ore matrix. Analyst: Shand (Levin, 1950).
2. Hornblende, dark ore matrix. Analyst: Oslund.
3. Hornblende, garnet rim. Analyst: Levin (Levin, 1950).

Furthermore, a new estimation was made of the mode of the dark ore.

Garnet Content.—It has been shown earlier how the size and frequency of garnet crystals vary within the ore body: in places, particularly along the southern limit of the mine, these crystals are irregular in shape and size; they

TABLE 4

BASIC ROCKS OF BARTON MINES. CHEMICAL ANALYSES

	A	A′	B	C
SiO_2	46.20	46.3	47.56	43.44
TiO_2	0.66	0.7	0.65	0.63
Al_2O_3	18.46	16.2	16.33	15.27
Fe_2O_3	1.77	2.2	0.54	2.81
FeO	9.42	9.4	11.13	11.42
MnO	0.15	0.1	0.16	0.17
MgO	9.87	11.8	11.03	14.58
CaO	8.91	9.2	8.01	7.90
Na_2O	2.71	2.7	2.52	1.87
K_2O	0.44	0.6	0.48	0.33
H_2O +	0.79	0.8	1.01	1.29
H_2O −	0.04	—	0.11	0.12
P_2O_5	0.08	—	0.28	0.04
CO_2	0.21	—	—	0.05
F	0.02	—	—	—
Total	99.71	100.00	99.81	99.92

A. Dark ore (porphyroblastic garnet amphibolite) Analyst: K. Oslund.
A′. Dark ore (as computed by Levin).
B. Corona-bearing olivine gabbro. Analyst: S. J. Shand (Shand, 1945).
C. Hornblendite. Analyst: D. Thaemlitz.

are irregularly scattered through the rock. The garnet content is certainly low although difficult to estimate. On the other hand, in the central part of the ore body, the garnets are uniform in size and shape and their distribution is more regular so that the garnet content can be estimated with a reasonable accuracy. The following results have been obtained: between 15 and 20 percent as measured on quarry walls; these values may be too high, for the garnets are the more friable part of the rock so that the fractures induced by mining tend to go through them rather than through the matrix; 14.5 ± 0.5 percent as measured with a polar planimeter on a large specimen that had been cut into slices.

Hornblende Shells.—It is easily seen that the volume of the shell increases with the volume of the enclosed garnet. However, the ratio of these volumes

TABLE 5

MODE OF THE DARK ORE MATRIX

	1	2	3	4	5
Hornblende	58.6	52.5	56	62.5	57.4
Plagioclase	36.8	34.9	29	27.0	31.9
Hypersthene	4.1	11.9	13	9.3	9.6
Biotite	0.3	0.4	1	—	—
Apatite	0.0	0.1	—	—	—
Magnetite	0.2	0.2	—	—	—
Total	100.0	100.0	99	98.8	98.9

1. Specimen analyzed (Table 4, A), which comes from central part of ore body. Garnet porphyroblasts (about 2″ across) make 15 percent of the rock.
2. Specimen from the southern limit of the mine; it contains a few garnets of variable shape and size. The garnet content is low.
3. Shaub's estimate.
4. Levin's estimate.
5. Average of 1, 2, 3 and 4.

is difficult to estimate. Only rather large garnets can be used because they only have a rim that is regular enough; also they must be cut through a diametral plane. About thirty garnets of variable size were selected. Their diameter was measured as well as the external diameter of the rim. It was found that, for twenty of these garnets, the volume ratio hornblende rim to enclosed garnet falls between 0.6 and 0.8. A few values were quite aberrant but no systematic variation with garnet diameter was suggested.

Matrix.—The mode of the matrix was measured by linear analysis under the microscope. Two specimens were used and for each specimen three sections cut at right angle to each other. The results are given in Table 5.

From these data, the mode of the dark ore is found to be:

Garnet	15%	
Rim hornblende	10%	
Matrix	75%	43% hornblende
		26% plagioclase
		6% hypersthene

TABLE 6

BASIC ROCKS OF BARTON MINES

	A	B	C
	Ionic percentages		
Si	44.1	42.8	40.3
Ti	0.5	0.4	0.4
Al	17.8	20.2	16.7
Fe +++	0.3	1.2	1.9
Fe ++	8.7	7.4	9.0
Mg	15.2	13.6	20.1
Ca	8.0	8.8	7.9
Na	4.6	4.8	3.3
K	0.6	0.5	0.4
P	0.2	0.1	0.0
Cations	100.0	99.8	100.0
OH	3.1	4.8	8.0
Anions	153	154	152
	Cationic norms		
Or	3.0	2.5	2.0
Ab	23.0	24.0	16.5
An.	31.5	37.2	32.5
Mt	0.4	1.8	2.8
Ilm	1.0	0.8	0.8
Wo	3.4	2.8	2.8
Hp	10.4	2.4	3.6
Ol	27.1	28.2	39.0
Ap	0.6	—	—
An/An + An	58	61	66
Mg/Fe + Mg	63	65	69

A. Corona-bearing olivine gabbro.
B. Dark ore.
C. Hornblendite.

The chemical composition calculated from this mode is in close agreement with the results of the chemical analysis (Table 6).

NATURE OF THE METAMORPHISM

The chemical analysis of Table 4 recast in ionic percentages according to the Barth-Eskola method (3) are given in Table 6, along with the cationic norms. From A to C, the analyses show an increase in the anorthite content of normative plagioclases, and in the magnesium iron ratio of normative olivine and pyroxene. Now, the corona-bearing olivine gabbro (A) is known to form the central part of a gabbro stock that grades toward the southern border into the dark ore (B), and then into the hornblendite (C). This suggests that B and C were derived from the border facies of the gabbro stock. A comparison of B and C with the "early border group" of the Skaergaard intrusion (25) shows that the differences observed between the chemical compositions of A, B and C are well within the limits of what can be ex-

pected on that basis. The only discrepancies are the increasingly high OH-content of A, B and C and the increasing degree of oxidation of iron in B and C.

Therefore, there is no reason to suppose that metasomatism has played an important role in the petrogenesis of the Barton Mines garnet ore. The metamorphism responsible for the formation of dark ore and hornblendite may be considered isochemical at least as a first approximation.

METAMORPHIC DIFFERENTIATION IN THE DARK ORE

From the chemical compositions of the constituent minerals and from the mode, the chemical compositions of the different parts of the dark ore can be calculated. The results of these calculations are presented in Table 7. Ionic percentages have been used throughout. To account for the different densities of the minerals involved, the following data have been used:

plagioclase:	0.0299 cation per cubic angstrom
honblende:	0.0356 cation per cubic angstrom
hypersthene:	0.0378 cation per cubic angstrom
diopside:	0.0368 cation per cubic angstrom
garnet:	0.0413 cation per cubic angstrom

These cationic densities were obtained from the unit cell dimensions and the structural formulas.

Table 7 clearly shows that the dark ore results from a metamorphic differentiation induced by the growth of garnet porphyroblasts. This differentiation involves the following ionic exchanges between the matrix on one hand, the garnets and their shells on the other:

Si + Na (+ possibly Ca) versus Fe (+ possibly Mg)

The resulting transformations are analyzed quantitatively below.

TABLE 7

COMPOSITION OF THE DARK ORE (IONIC RATIOS)

	Plagio. (analyzed)	Hypersthene (optics)	Matrix hornblende (analyzed)	Rim hornblende (analyzed)	Average garnet	Matrix (calcul.)	Garnet + shell (calcul.)	Dark ore (calcul.)	Dark ore (analyzed)
Si	2.49	1.00	6.16	6.35	3.00	43.0	38.5	41.8	42.8
Ti	—	—	0.12	0.12	—	0.5	0.3	0.1	0.4
Al	1.49	—	2.63	2.26	1.96	20.2	20.8	20.4	20.2
Fe +++	0.02	—	0.42	0.37	0.04	1.8	1.2	1.6	1.2
Fe ++	—	0.30	1.19	1.14	1.32	5.4	13.1	7.6	7.4
Mn	—	—	0.02	0.01	0.03	0.1	0.2	0.1	—
Mg	0.01	0.70	2.85	3.12	1.20	12.9	16.7	14.0	13.6
Ca	0.47	—	1.59	1.65	0.45	9.3	7.3	8.7	8.8
Na	0.51	—	0.76	0.72	—	6.3	1.6	5.0	4.8
K	0.01	—	0.11	0.12	—	0.5	0.3	0.4	0.5
Cations	5.00	2.00	15.85	15.86	8.00	100.0	100.0	100.0	99.7
OH	0.02	—	1.52	1.12	—	6.1	2.5	5.1	4.8
F	—	—	0.04	0.14	—	0.2	0.3	0.2	—
Cl	—	—	0.01	—	—	—	—	—	—
Anions	8.00	3.00	24.00	24.00	12.00	154.0	150.5	153.0	154.0

Three separate processes, which take place concurrently, contribute to the formation of the dark ore: a) the garnet porphyroblast grows at the expense of the hornblende rim; b) the rim grows at the expense of the matrix by a volume 70 percent larger; c) reactions take place within the matrix. Table 8 shows the ionic exchanges required when the garnet porphyroblast grows by a volume corresponding to 100 cations. The ions moving outward are taken with a positive sign.

Important ionic exchanges take place at the boundary of a growing garnet (Table 8, column 1). Large quantities of aluminum ions move inwards so that the growth of the garnet requires a continuous supply of aluminum; with regard to this, it is interesting to note (Table 3) that the rim horn-

TABLE 8

IONIC EXCHANGES DURING GROWTH OF PORPHYROBLASTS

	1	2	3
Si	+2.6	+5.6	+8.2
Ti	+0.8	−0.5	+0.3
Al	−10.2	+9.9	−0.3
Fe +++	+1.8	−1.0	+0.8
Fe ++(+ Mn)	−9.6	−3.0	−12.6
Mg	+4.7	−11.6	−6.9
Ca	+4.8	−2.0	+2.8
Na	+4.5	+2.9	+7.4
K	+0.8	−0.5	+0.3
OH	+7.1	−1.6	+5.5
Anions	+1.3	+4.0	+5.3

1. Ions exchanged at the boundary of a growing garnet when this garnet grows at expense of rim by a volume corresponding to 100 cations.
2. Ions exchanged during the corresponding growth of the rim at expense of matrix.
3. Corresponding changes in the composition of matrix; this is equal to the total exchange at boundary of rim.
+ refer to ions diffusing from the garnet outwards.
− refer to ions diffusing from the matrix towards the garnet.

blende is poorer in aluminum than the matrix hornblende so that a compositional gradient exists along which aluminum ions are carried from the matrix towards the porphyroblast. The same remark can be made about the silicon and the magnesium ions, which move outwards. On the other hand, important diffusions of iron, calcium and sodium ions take place along gradients that are apparently too small to be displayed by chemical analyses.

The aluminum ions diffusing through the rim towards the garnet are supplied by the transformation that occurs at the boundary of the rim—the growth of the rim at the expense of the matrix (Table 8, column 2). This is why the aluminum content of the matrix does not change during the growth of the garnet. Other ions, such as ferrous iron and magnesium ions must be supplied by reactions occurring within the matrix.

The changes in the chemical composition of the matrix during garnet growth are easily found to be the algebraic sum of the ionic exchanges required by the growth of the garnet and by the growth of the rim (column 3).

These changes suggest that the following mineralogical transformations take place within the matrix:

1. During garnet growth, OH^- ions diffuse towards the matrix; this can be accounted for only by an increasing hornblende content of the matrix.

2. This increase requires a supply of aluminum and calcium. Since no or few Al and Ca ions diffuse towards the matrix, these ions must be supplied by the anorthite component of the matrix plagioclase. On the other hand, the diffusion of equal amounts of Si and Na ions towards the matrix can be accounted for only by an increase of the albite component of this plagioclase.

3. Fe^{++} and Mg ions diffuse away from the matrix. Since the hornblende content is increasing, this must mean a decreasing orthopyroxene content, which is also suggested by a comparison between the modes of the matrix in garnet-rich and garnet-poor specimens of dark ore (Table 5).

4. The Fe/Mg + Fe ratio in the matrix decreases. Therefore hornblende and hypersthene are becoming more magnesian. This change, which is to be correlated with Levin's observation that garnet porphyroblasts are less pyropic at their center than at their periphery, suggests that the dark ore has formed during a period of rising temperature.

In short, the mineralogical transformations taking place within the matrix of the dark ore during the growth of the porphyroblasts can be written:

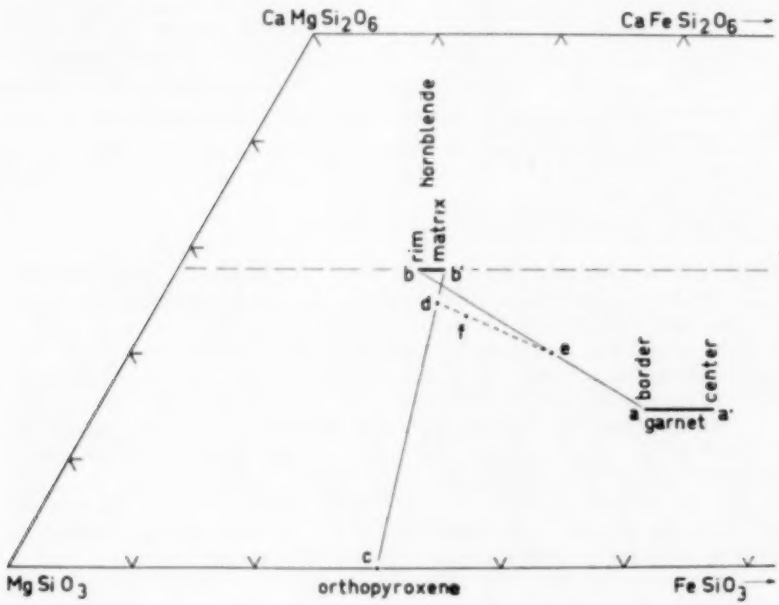


FIG. 9. Chemical composition of the Barton Mines dark ore.

$$\text{Anorthite} + \text{orthopyroxene} + \text{Si} + \text{Na}\ (+\text{Ca}) + \text{OH}^- \rightarrow \text{hornblende} + \text{albite} + \text{Fe}(+\text{Mg})$$

The chemical composition of the ferromagnesian minerals of the Barton Mines dark ore are plotted in Figure 9 on a triangular diagram. The range in the composition of garnet is shown by a horizontal line (*aa'*) since, according to Levin, the calcium content does not vary from the core to the border of a porphyroblast. The range in the composition of hornblende is also represented by a horizontal line (*bb'*) since the calcium content of the

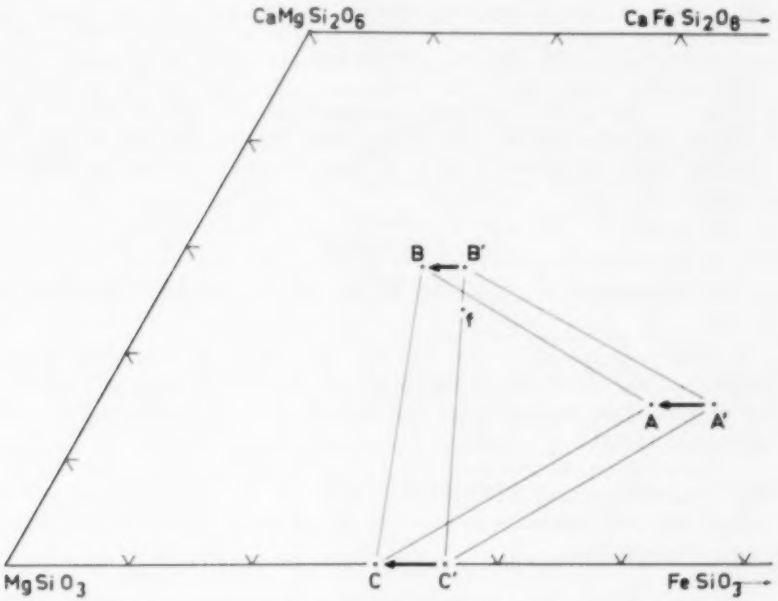


FIG. 10. Schematic evolution of the Barton Mines dark ore with rising temperature.

rim and matrix hornblendes are almost the same. The tie-lines *ab* and *b'c* have been drawn between minerals that can be presumed to be in chemical equilibrium.

If the plagioclase content is neglected, the dark ore matrix can be represented by a point *d* situated on tie line *b'c* close to *b'* since in the matrix, hornblende is much more abundant than orthopyroxene. Similarly, the composition of the garnet plus shell part of the rock is represented by a point *e* on *ab*, and the composition of the dark ore itself by a point *f* situated on *de*, a quarter of the distance away from *d*.

More schematically, by neglecting the disequilibria involved in the zoning of garnet and the varying hornblende composition, the dark ore can be represented by a point f within a tie-line triangle A B C on the same diagram (Fig. 10). The shift of this triangle from a former position A'B'C' to A B C represents the mineralogical transformations in the dark ore during the growth of porphyroblasts; increase in hornblende content and decrease in hypersthene while all minerals become more magnesian. It is most likely that this shift was caused by rising temperature.

There are differences between the schematic evolution of the dark ore pictured in figure 10 and the actual evolution. These differences are precisely related to the disequilibria displayed in the rock and to the special structure that results from them. The cause of these disequilibria is obviously the abnormally large size of the garnets or, in other words, their small number. This feature of the dark ore is indeed puzzling because garnet does not seem to be a crystal whose nucleation is particularly difficult; rocks sprinkled with small garnet crystals are quite common. It may be that the nucleation requires a lesser degree of oversaturation in rocks undergoing plastic flow.

CONCLUSION

The petrogenesis of the Barton Mines dark ore can be summarized as follows:

During a period of orogenic folding, and under conditions of intense plastic flow, the ophitic olivine gabbro became transformed into an amphibolite carrying some plagioclase and orthopyroxene. This transformation was isochemical except for a slight increase in the water content. At the time when the componental movements were waning, garnet began crystallizing. Later changes consisted of adjustments to the rising temperature and of a metamorphic differentiation induced by the growth of abnormally large garnet porphyroblasts.

ACKNOWLEDGMENTS

This work is part of a dissertation presented to the Faculty of Princeton University in candidacy for the degree of Doctor of Philosophy. It is a pleasure to acknowledge my great indebtedness to Professor A. F. Buddington whose constant interest throughout all stages of this study I have deeply appreciated. I am also grateful to Professors H. H. Hess, H. D. Holland and J. C. Maxwell for stimulating discussions and helpful criticisms.

The cost of the field expenses and of the chemical analyses was covered by grants from the Eugene Higgins Trust allocated to Princeton University, and from the New York State Museum and Science Service.

The chemical analyses were made in the Laboratory for Rock Analysis at the University of Minnesota.

I am indebted to Mr. Hudson Barton and the staff of the Barton Mines Corporation, particularly to Mr. T. Leonard, for many facilities during field studies in 1954 and 1955.

My thanks are also due to Mrs. M. H. Krieger for permission to consult an unpublished manuscript.

UNIVERSITÉ LOVANIUM,
LÉOPOLDVILLE (BELGIAN CONGO),
April 20, 1959

REFERENCES

1. Balk, R., 1931, Structural geology of the Adirondack anorthosite: Min. pet. Mitt., v. 41, p. 308–434.
2. ——, 1932, Geology of the Newcomb quadrangle: New York State Mus. Bull. 290.
3. Barth, T. F. W., 1955, Presentation of rock analyses: Jour. Geology, v. 63, p. 348–363.
4. Bartholomé, P. 1956, Ph.D. Thesis, Princeton.
5. ——, 1958, The Gore Mountain garnet deposit, New York. Structure and Petrography: Studia Universitatis Lovanium, Faculté des Sciences, n°6.
6. Brogger, W. C., 1934, The south Norwegian hyperites and their metamorphism: Skrifter utgitt av Det Norske Videnskaps-Akademi i Oslo, Mat-Nat Klasse, 421 p.
7. Buddington, A. F., 1939, Adirondack igneous rocks and their metamorphism: Geol. Soc. America Memoir 7, p. 1–354.
8. ——, 1948, Origin of granitic rocks of the northwest Adirondacks in "Origin of granite": Geol. Soc. America Memoir 28, p. 1–138.
9. ——, 1952, Chemical petrology of some metamorphosed Adirondack gabbroic, syenitic and quartz syenitic rocks: Am. Jour. Sci., Bowen Vol., p. 37–84.
10. ——, Fahey, J., and Vlisidis, A., 1955, Thermometric and petrogenic significance of titaniferous magnetite: Am. Jour. Sci., v. 253, p. 497–532.
11. Gorai, M., 1951, Petrological studies on plagioclase twins: Am. Mineralogist, v. 36, p. 884–901.
12. Hess, H. H., 1952, Orthopyroxenes of the Bushveld type, ion substitutions and changes in unit cell dimensions. Am. Jour. Sci., Bowen Vol., p. 173–188.
13. ——, and Poldervaart, A., 1951, Pyroxenes in the crystallization of basaltic magma: Jour. Geology, v. 59, p. 473–489.
14. Krieger, M. H., 1937, Geology of the Thirteenth Lake quadrangle: New York State Mus. Bull. 308.
15. Lacroix, A., 1889, Contributions à l'étude des gneiss à pyroxène et des roches à wernérite: Soc. franç. minéralogie Bull., v. 12, p. 282–348.
16. Levin, S. B., 1950, Genesis of some Adirondack garnet deposits: Geol. Soc. America Bull., v. 61, p. 519–565.
17. Miller, W. J., 1912, The garnet deposits of Warren County, New York: ECON. GEOL., v. 7, p. 493–501.
18. ——, 1914, Geology of the North Creek quadrangle: New York State Mus. Bull. 170.
19. ——, 1938, Genesis of certain Adirondack garnet deposits: Am. Mineralogist, v. 23, p. 399–408.
20. Murthy M. V. N., 1958, Coronites from India and their bearing on the origin of coronas: Geol. Soc. America Bull., v. 69, p. 23–38.
21. Shand, S. J., 1945, Coronas and coronites: Geol. Soc. America Bull., v. 56, p. 247–266.
22. Shaub, B. M., 1949, Paragenesis of the garnet and associated minerals of the Barton mine near North Creek, New York: Am. Mineralogist, v. 34, p. 573–582.
23. Subramanian, A. P., 1956, Mineralogy and petrology of the Sittampundi complex, Salem district, Madras state, India: Geol. Soc. America Bull., v. 67, p. 317–390.
24. Turner, F. J., 1947, Observations on twinning of plagioclase in metamorphic rocks: Am. Mineralogist, v. 36, p. 581–589.
25. Wager, L. R., and Deer, W. A., 1939, The petrology of the Skaergaard Intrusion, Kangerdlugssauk, East Greenland: Meddelelser om Grönland, v. 105, p. 1–352.
26. Wentorf, R. H., Jr., 1956, The formation of Gore Mountain garnet and hornblende at high temperature and pressure: Am. Jour. Sci., v. 254, p. 413–419.

Economic Geology
Vol. 55, 1960, pp. 278–310

MANGANESE OXIDES AND ASSOCIATED MINERALS OF THE NSUTA MANGANESE DEPOSITS, GHANA, WEST AFRICA

R. K. SOREM AND E. N. CAMERON

CONTENTS

	PAGE
Abstract	278
Introduction	279
Acknowledgments	279
Previous investigations	280
Methods employed in the present investigation and materials studied	281
The Nsuta manganese deposits	281
Description of the ores	282
Megascopic features	282
Microscopy of the ores	284
Genetic types of ores	284
Replacement ore	285
Ore formed by cavity filling or residual concentration of manganese oxides	289
Mineralogy of the ores	290
General statement	290
Nsuta MnO_2	290
Cryptomelane	292
Pyrolusite	295
Lithiophorite	295
Distinction of the manganese oxide minerals in polished surfaces	297
Goethite	298
Paragenetic sequence and stages of formation	298
X-ray diffraction studies	300
General	300
Standard patterns	300
Cryptomelane, pyrolusite, and lithiophorite	300
Nsuta MnO_2	300
Terminology	307
Summary	308
References	309

ABSTRACT

Mineragraphic and X-ray investigations of manganese ore from the highly productive deposits of Nsuta, Ghana, indicate that the principal manganese oxide minerals, in order of decreasing abundance, are Nsuta MnO_2, cryptomelane, pyrolusite, and lithiophorite. Goethite is closely associated with manganese oxides in some of the ore. Nonmetallic impurities identified are muscovite, quartz, garnet, zircon, and amphibole.

X-ray diffraction data indicate that Nsuta MnO_2 is a discrete mineral

or mineral group, with no direct relation to pyrolusite or ramsdellite. Powder patterns given by Nsuta MnO_2 also differ from those reported for the artificial manganese dioxide gamma-MnO_2. One type of Nsuta MnO_2 gives a pattern closely resembling that of rho-MnO_2, a chemical product, but the *d* spacings and relative intensities of certain lines are not identical.

Oxide-rich ore was formed by three principal mechanisms: replacement of rocks rich in quartz, muscovite, garnet, and perhaps other minerals; filling of fractures and other openings; and leaching of impurities from low-grade ore with or without addition of manganese oxides. The three types of ore are intimately related and consist predominantly of Nsuta MnO_2 and cryptomelane. Pyrolusite and lithiophorite are abundant, however, in certain specimens of replacement ore and cavity-filling ore. Goethite is present locally in all three types of ore.

Nsuta MnO_2 and cryptomelane are early minerals in most specimens, but there is no fixed paragenetic sequence of the oxide minerals. Two or more generations of various oxides are present in many specimens.

The mineral assemblage of the ores, the paragenetic sequence, and the textures and structures all appear to be consistent with supergene deposition of the manganese oxides. The origin of a mineral deposit can seldom be determined solely by laboratory study, but certainly these ores are of a kind that would be expected if meteoric water, varying intermittently in supply and composition, were the principal agent of oxide formation.

INTRODUCTION

THE manganese deposits of Nsuta, in Ghana, discovered in 1914, have been a major source of metallurgical and battery-grade manganese ores for more than thirty-five years. Descriptions of the deposits have been published from time to time since 1915, but the mineralogy of the ores has not been investigated fully. This paper gives results of a detailed optical and X-ray study of suites of ore specimens from various parts of the Nsuta deposits. The mineralogy and textures of the ores are described, and stages in the formation of the oxides are discussed.

Acknowledgments.—The laboratory studies reported are part of an investigation of manganese ores being made in the Laboratory of Economic Geology at The University of Wisconsin under a research grant from Union Carbide Corporation. We gratefully acknowledge this support. The study was undertaken at the suggestion of Mr. Dean F. Frasché, Manager, Mineral Survey Department, Union Carbide Ore Company, and has benefited steadily from his advice and assistance in procuring materials and equipment. Mr. Robert A. Specker, National Carbon Company, Cleveland, Ohio, has furnished materials and information, and he and other members of the staff of the Edgewater Laboratory have given much valuable advice. Mr. John A. Straczek, of Union Carbide Ore Company, furnished an excellent suite of specimens from Nsuta, together with information as to their occurrence in the field. Conferences with Mr. Straczek and Mr. H. R. Spedden, also of Union Carbide Ore Company, have yielded essential background information. To all these men we wish to express our appreciation.

At the University, Prof. S. W. Bailey has been a generous advisor in matters connected with interpretation of X-ray data.

PREVIOUS INVESTIGATIONS

The Nsuta manganese deposits were first mentioned in two brief reports by the discoverer of the deposits, A. E. Kitson (14, 15), and were described more fully later by Kitson (16). Bishopp and Hughes (1) wrote a comprehensive paper on Gold Coast (Ghana) manganese deposits that includes an account of the Nsuta deposits and a discussion of the genesis of the ores and associated rocks. They concluded that the ores were all formed by enrichment, mainly in recent near-surface environments, of low-grade manganiferous sediments. Junner (12, 13) argued that the large ore-bodies at Nsuta are of Precambrian age. Service (24) supported Junner's conclusions on the basis of detailed study and mapping of the deposits. Service's report contains a mineragraphic description, by J. A. Dunn, of a suite of specimens of the manganese ores. Dunn reported that the ores consist of pyrolusite, psilomelane, goethite, and manganese garnet, together with a little quartz and halloysite, and a mineral he designated Component 3. From his description of the properties of this mineral, Component 3 is evidently the lithiophorite reported by Delano (4) and described in the present report.

Except for Dunn's work, no mineragraphic investigation of the Nsuta ores has been made during the past 20 years, so far as we know. Mineralogical data based upon X-ray work have appeared occasionally, however, in diverse publications. Schossberger (23) reported the discovery in "West African pyrolusite" of material which gave an X-ray powder pattern similar to that of artificial "gamma-MnO_2" (Glemser, 9), and McMurdie (18) corroborated this identification and also reported finding ramsdellite in Nsuta ores. McMurdie and Golovato (19) declared further that "Gold Coast ore is largely" of the gamma-MnO_2 "form." Cole et al. (3), meanwhile, concluded that the major constituent of the Nsuta ore which they studied was a specific variety of gamma-MnO_2 which they designated type I; they also identified pyrolusite and questionable cryptomelane as minor components. Delano reported (4) that still another mineral, lithiophorite, was present in the Nsuta ores, and stated that the principal mineral in the ores, called by others gamma-MnO_2, was poorly crystallized ramsdellite. He reported that common "impurities" in the Nsuta battery ore are cryptomelane, pyrolusite, lithiophorite, quartz, and clay minerals.

Except for Dunn, the investigators mentioned above appear to have relied on X-ray diffraction studies, with or without chemical analyses, for mineralogical determinations. Additional X-ray and chemical data have been provided in numerous papers concerned primarily with dry battery research. These data are useful but have added little to the basic knowledge of the mineralogy of the ores. It is of interest, however, that the Signal Corps Engineering Laboratories, U. S. Army, in recent years, have used the term "rho-MnO_2" for a synthetic product which they consider to have an X-ray pattern identical to that of the major component of Nsuta ore (Nye, 20).

METHODS EMPLOYED IN THE PRESENT INVESTIGATION AND MATERIALS STUDIED

The present investigation combines microscope study of polished surfaces with mineral identification by x-ray powder camera techniques. This general procedure has been used in ore investigations for many years, but its application to the study of manganese oxide ores evidently has been limited. Slabs for polished surfaces are cut from each ore specimen to include all recognizable textural and mineralogical types. A photograph is then made of each polished surface in reflected light, after which mineragraphic examination is begun. A preliminary determination of the number of mineral components is made and all components of questionable identity are marked for X-ray. These components are sampled under the microscope by chipping with a diamond pencil. Thus, it is known at the outset whether a given specimen for X-ray study consists of one mineral or a mixture of two or more minerals. Monomineralic samples are desired for X-ray and can be obtained except in uncommon cases in which banding or intergrowths are very intricate. The location of the point from which each X-ray sample is taken is plotted on the photograph of the surface. The X-ray specimen is mounted on a glass fiber with shellac and exposed in a powder camera.

The importance of following the method described above can scarcely be overemphasized. All Nsuta ore specimens examined are mixtures of two or more oxides, commonly with other minerals. In the great majority of specimens, intermixture is on such a fine scale that X-ray samples taken at random, without close control by means of polished surfaces, are inevitably mixtures. Satisfactory interpretation of diffraction patterns of such mixtures is in many cases difficult or impossible. It seems probable that much of the confusion in the literature over the X-ray diffraction data for manganese oxides is due to the fact that the purity of the materials submitted for X-ray is unknown.

The materials studied consist of a large variety of miscellaneous samples of Nsuta ores, together with a suite of specimens collected at the deposit by Mr. J. A. Straczek. The materials studied are thought to include the principal types of ores present at the locality, but it is unlikely that all variants of the ore are represented in our collections. The writers feel confident that the essential mineralogy of the ores currently worked at the mine is indicated by the present work, but studies of additional samples will undoubtedly add to the data presented.

Source rocks from which the manganese oxide ores have formed by enrichment are poorly represented in our collections. A few notes are given on this subject, but a general discussion of source rocks is beyond the scope of this paper.

THE NSUTA MANGANESE DEPOSITS

As described by Service (24), the ore bodies at Nsuta occur in a sequence of phyllites 375 to 400 feet thick in the Precambrian Birrimian series. The sequence is deformed into near-isoclinal folds trending about N 15° E. In-

cluded in the phyllite are beds of gondite (quartz-spessartite rock), formed by metamorphism of manganiferous sediments. Service concluded that the ore bodies are sedimentary lenses rich in manganese oxides, but he recognized that Recent or late Tertiary laterisation of the ore bodies has taken place and that the gondites beneath the ore bodies have locally been enriched in oxides.

According to Service, a typical ore body in vertical section begins at the top with detrital ore, which overlies hard, "lateritic" ore. Beneath the lateritic ore is high-grade, porous "black ore," which passes downward into average grade porous "black ore." Argillaceous impurities increase downward in the "black ore" zone, both in cavities and locally in definitely sedimentary bands. "The percentage of argillaceous matter increases markedly as the water table is approached, the ore in some of the lower adits being interbedded with slightly weathered beds of phyllite and tuff." In the vicinity of the water table, gonditic ores show much less leaching of silica than above the water table.

Despite Service's conclusion as to the origin of the ores, many of the features he describes suggest a profile of the type due to residual weathering. The origin of the deposits, however, is currently the subject of debate among geologists familiar with the mine.

The ore bodies originally cropped out in a series of hills termed hills A, B, C, D, and E. For the locations of the hills, the reader is referred to Service's map (24, Pl. I).

DESCRIPTION OF THE ORES

Megascopic Features.—As indicated in the descriptions given by Service and Dunn (24), the ores display a great variety of textural and structural features. They range from hard material, either massive or distinctly layered, to soft pulverulent ores of the "wad" type. In the harder ores, layering is of two types—original sedimentary lamination and concretionary or colloform layering. Sedimentary layering in the specimens studied is due to variations in the ratio of quartz and silicates to manganese oxides. Concretionary layering is superimposed on sedimentary layering in some specimens. The distinction between this and colloform banding of materials deposited in cavities is somewhat arbitrary. Colloform-textured ore shows the usual range of mammillary and botryoidal forms. Such ores have numerous cavities lined with colloform material, or, in some specimens, with crystals of pyrolusite up to 0.5 cm in length. Veinlets of oxides healing fractures are visible in sawn specimens of all types of ores. Some specimens of black ore of the "wad" type are composed entirely of soft, pulverulent black oxides; others have thin ribs of harder material.

Quartz occurs as discrete grains or aggregates of grains, as veinlets, and as veinlets dismembered by fracturing. The quartz veinlets are merely small representatives of the large veins of quartz cutting the black ore zones (24) in the working faces of the mine. A few specimens differ from the types described above in that they consist of massive granular quartz cut by a network of veinlets of manganese oxides.

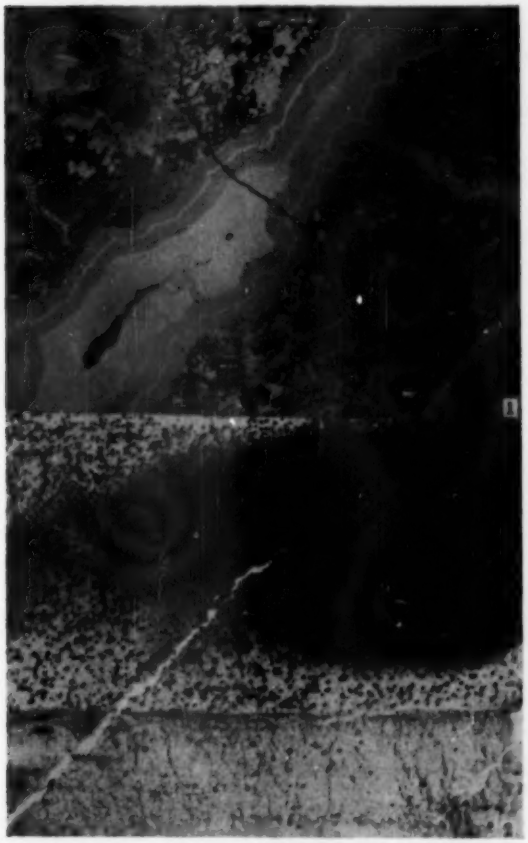


FIG. 1. Polished surface of replacement ore, plain light, × 50. Micaceous rock replaced extensively by Nsuta MnO_2 (white), which in many places separates muscovite grains (black) along the cleavage. A complex symmetrically layered veinlet, made up Nsuta MnO_2 (white) and cryptomelane (medium gray), cuts the replacement ore in a northeasterly direction. At lower right is an irregular veinlet of Nsuta MnO_2.

FIG. 2. Polished surface of replacement ore. Plain light, × 4. Garnetiferous rock partly replaced by Nsuta MnO_2 (white, gray). Garnet (small spots) is most abundant in upper part of surface. Dark lenticular mass at upper right is unreplaced rock made up of garnet in a matrix of quartz, iron oxides and fine-grained oolites of an unidentified mineral. Specimen collected by J. A. Straczek from north end of pit, bottom level, Hill A.

MICROSCOPY OF THE ORES

Genetic Types of Ores.—On the basis of mode of formation, three general types of material can be distinguished in the ore specimens examined. The first consists of manganese oxides, with or without goethite, that have been

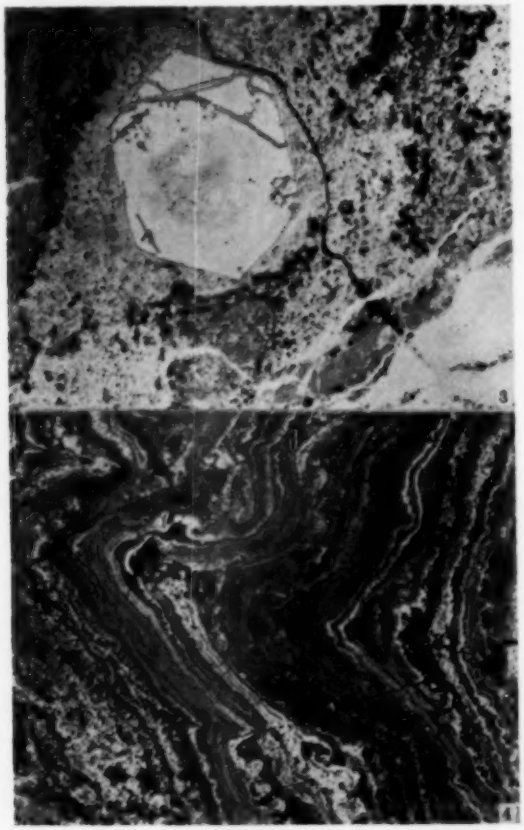


FIG. 3. Polished surface of replacement ore. Plain light, × 50. Fine-grained mica-quartz-garnet rock is largely replaced by Nsuta MnO_2 (white) and lithiophorite (medium gray). Gray veinlet at the lower right, trending northeast, is goethite. Six-sided garnet crystal outlined and cut by thin veinlets of cryptomelane (medium gray) is almost totally replaced by Nsuta MnO_2.

FIG. 4. Polished surface of laminated replacement ore. Plain light, × 4. Deformed rock in which many laminae are largely replaced by Nsuta MnO_2 (white, light gray) and goethite (medium gray). Dark gray—non-opaque minerals (in part quartz and argillaceous material) and Bakelite filling pore spaces. Wad-type ore collected by J. A. Straczek from lower mining level, Hill D, north crest.

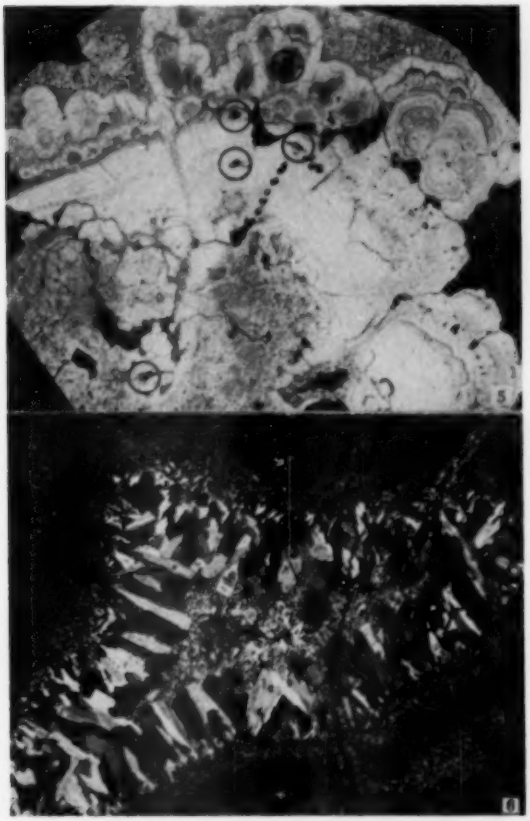
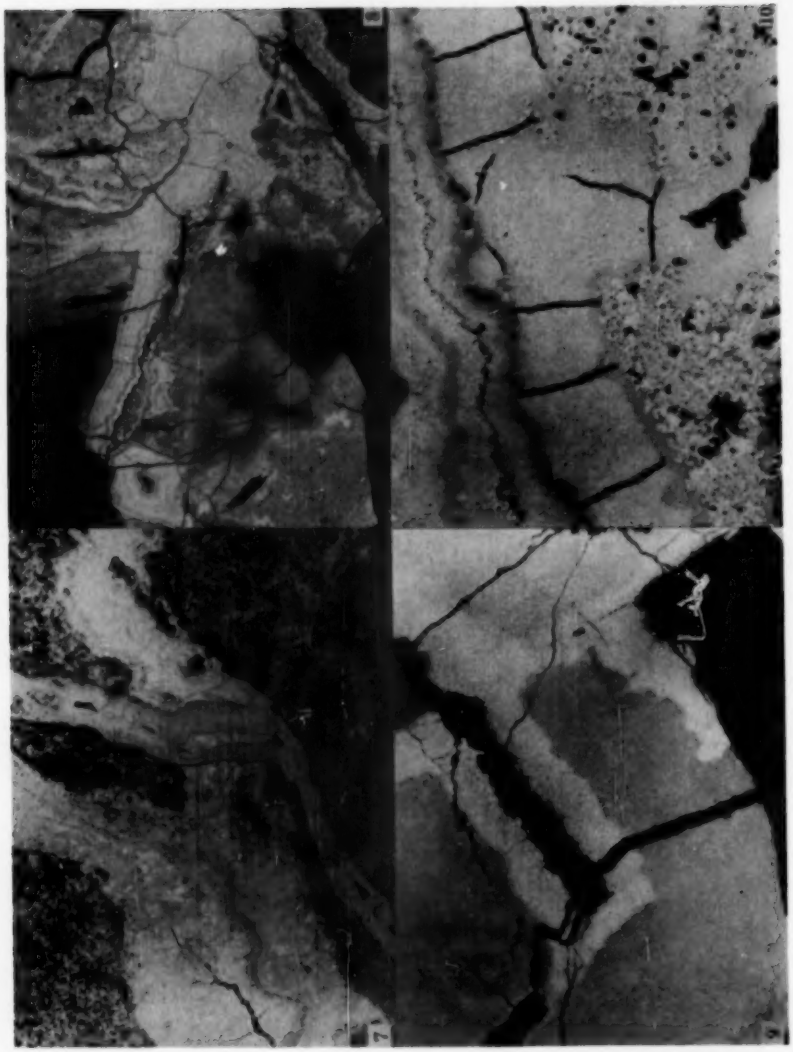


FIG. 5. Polished surface of colloform cavity ore encrusting replacement ore. Plain light, × 4. Broad colloform layers (light gray) across the center of the specimen are pyrolusite, with minor Nsuta MnO_2. Botyroidal forms outside these are largely Nsuta MnO_2, some layers of which show conspicuous transverse cracks. Thin cryptomelane layers (medium gray) separate the Nsuta MnO_2 layers conformably. The outer crust consists of well-formed pyrolusite. Late pyrolusite veinlets fill fractures in the earlier oxides. Replacement ore in the southwest quadrant (gray) is largely Nsuta MnO_2. Each circle marks the location of an X-ray sample. The dark spot is the pit left after excavation of the sample.

FIG. 6. Polished surface showing symmetrically layered veinlet. Crossed polars, × 55. Pyrolusite, with comb structure, enclosed by layers of Nsuta MnO_2 and enclosing a core of unusually coarse-grained, mosaic-textured Nsuta MnO_2. Thin dark band bordering the coarse-grained pyrolusite is probably very fine-grained Nsuta MnO_2, but some cryptomelane may be intermixed.



FIGS. 7–10.

formed by replacement or partial replacement of pre-existing rock. The second consists of material that has been formed by the filling of cavities and fractures. The third consists of material left behind after leaching of soluble non-manganiferous material and is essentially residual ore. The three types of ore materials are closely associated, and most samples examined are mixtures of the three in various proportions. In most specimens the distinction between the first two types is a simple matter, but in some specimens or parts of specimens, replacement ore is not sharply distinct from residual ore.

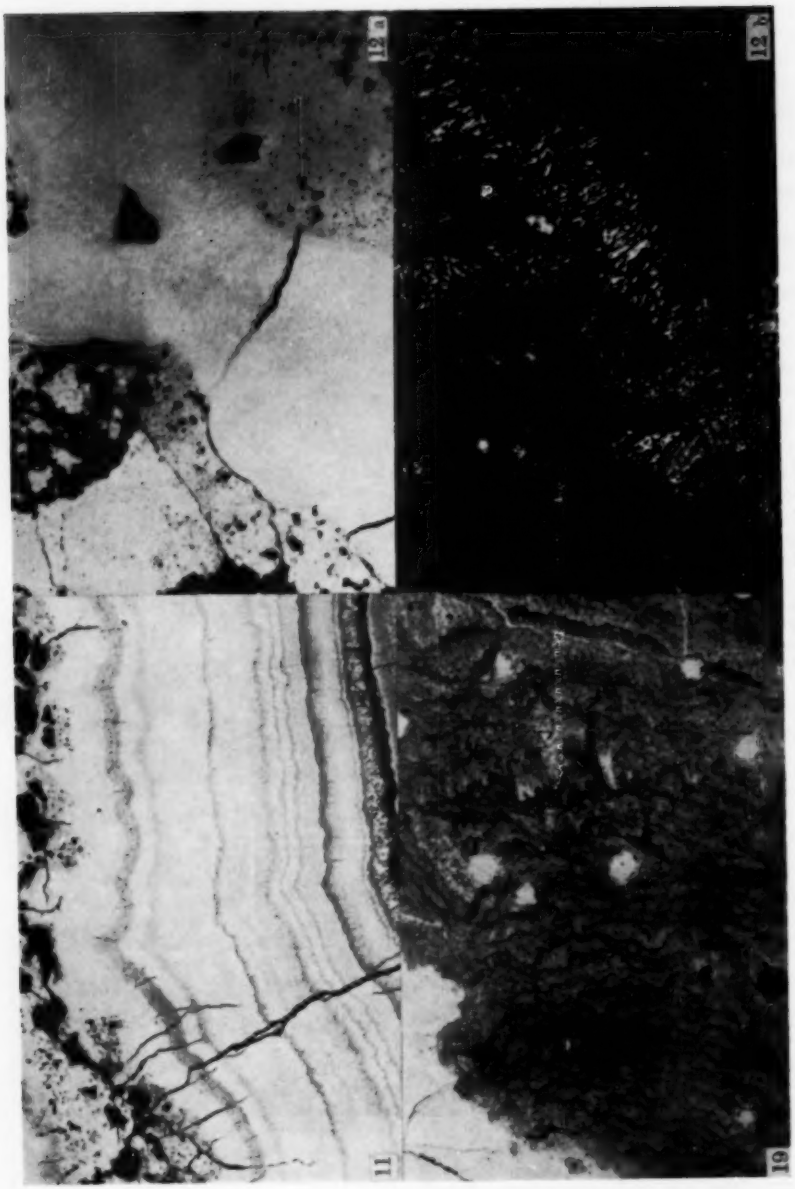
Replacement Ore.—In polished surface, replacement ore is characterized by the presence of numerous relicts of muscovite, quartz, and garnet in various proportions. In the most common type, the relicts are minute flakes of muscovite (Fig. 1), forming a few percent to more than 50 percent of the ore. In some muscovitic ore, quartz and garnet are absent or present in minor amounts. In others, quartz and garnet are abundant. The second most abundant type of replacement ore consists of quartz, garnet, and fine-grained manganese oxides. The manganese oxides have formed in part by replacement of garnet and quartz, but in large part the oxides appear to have formed at the expense of another fine-grained mineral that we are unable to identify in the materials at hand. In the parts of the rock least replaced by man-

FIG. 7. Polished surface showing veinlets in replacement ore. Plain light, × 55. Fine-grained micaceous rock largely replaced by Nsuta MnO_2 and lithiophorite (white and dark gray) is cut by complex veinlets of different ages. Earlier veinlet is broad at left and divides into two branches upward to right. This veinlet is largely Nsuta MnO_2, but on it is superimposed an intricate network of minor veinlets (medium gray) which in part may be cryptomelane. Later veinlet, largely cryptomelane, cuts both matrix replacement ore and a branch of the larger veinlet.

FIG. 8. Polished surface of replacement ore cemented by colloform cavity-filling oxides. Plain light, × 5.7. Irregular rock fragment largely replaced by manganese oxides (southwest quadrant) shows diffuse banding of cryptomelane (medium gray) and Nsuta MnO_2 (light gray). Another fragment (northeast quadrant) is replaced largely by Nsuta MnO_2. Colloform cementing material consists principally of thicker layers of Nsuta MnO_2 (light gray) alternating with thinner layers of cryptomelane. Specimen collected by J. A. Straczek from lower mining level, Hill D, north crest.

FIG. 9. Polished surface showing complex cavity-filling ore. Plain light, × 100. Massive cryptomelane (medium gray) partly replaced along fractures by Nsuta MnO_2 (white). Veinlets of lithiophorite (dark gray) fill fractures in Nsuta MnO_2 and in cryptomelane. Lithiophorite-Nsuta MnO_2 contact is irregular and suggests partial replacement of the Nsuta MnO_2. Large cavities are lined with a crust of lithiophorite. Black areas are Castolite. Specimen collected by J. A. Straczek from near bottom level and north end of pit, Hill A.

FIG. 10. Polished surface showing cavity-filling ore and replacement ore. Plain light, × 100. Replacement ore in lower half of photograph is relatively coarse-grained mosaic pyrolusite (white). Wide band immediately above and cutting the the pyrolusite downward is Nsuta MnO_2 (light gray). This band has a thin selvage of cryptomelane (medium gray). Note irregular contact of cryptomelane and pyrolusite, and an island of pyrolusite in the Nsuta MnO_2 layer to the north-northeast of the center, where a nearly vertical crack ends. Outside main layer of Nsuta MnO_2 lie thin bands of fine-grained cryptomelane, pyrolusite, and Nsuta MnO_2. Transverse cracks commonly found in colloform layers of Nsuta MnO_2 are well shown in the broad band.



FIGS. 11, 12a, 12b and 19.

ganese oxides, a pale yellow mineral of low birefringence forms minute (less than .05 mm) but prominent oölites. Replacement begins with oxidation and apparent conversion of these oölites to iron oxides (goethite?). This stage is followed by replacement of the goethite (?) by manganese oxides. This type of replacement is found in the specimen illustrated in Figure 2. In advanced stages, quartz and garnet show various degrees of replacement by manganese oxides (Fig. 3).

The nature of the original rock represented in the muscovitic replacement ore is not indicated in the specimens examined. Both massive and well-layered rocks are suggested. Many aggregates of mica flakes are deformed, and folded primary lamination is preserved in some specimens (Fig. 4).

The manganese oxides in replacement ores are fine-grained; the individual particles are commonly measurable in microns. In extreme examples, the oxides approach the amorphous state and are weakly anisotropic to sensibly isotropic.

Ore Formed by Cavity Filling or Residual Concentration of Manganese Oxides.—Most of the ore formed by cavity filling shows colloform banding on a fine scale. The bands differ in composition or texture, or both. In many specimens, colloform material has been deposited around nuclei consisting of fragments of replacement ore (Fig. 5); in fact, this is the most common structural type of ore in the suite of specimens studied. The colloform material now binds the fragments together.

Veinlets have various structures. The most common are veinlets that show symmetrical colloform banding (Fig. 1), but symmetrical comb structure

---

FIG. 11. Polished surface of colloform cavity-filling ore. Plain light, × 65. Nsuta MnO_2 makes up most of the wide multi-layered band. It appears white to light gray depending on grain size, grain shape, and degree of preferred orientation. Numerous dark gray bands are composed largely of fine-grained cryptomelane. At bottom is relatively coarse-grained layer of Nsuta MnO_2 with mosaic texture. In upper part of photograph, beginning at the pitted zone, is replacement ore showing diffuse banding of Nsuta MnO_2 and cryptomelane. Small black spots are non-opaque mineral grains. Specimen collected by J. A. Straczek from lower mining level, Hill D, north crest.

FIG. 12a. Polished surface showing cavity filling in replacement ore. Plain light, × 150. Matrix is a granular rock largely replaced by Nsuta MnO_2 (light gray). Non-opaque grains are irregular black spots. Irregular mass of Nsuta MnO_2 fills cavity in central part of photograph; Nsuta MnO_2 in large part shows preferred orientation of platy grains roughly normal to the cavity walls. Specimen collected by H. R. Spedden from contact of "black ore" zone at Nsuta.

FIG. 12b. Same field as in Figure 12a but photographed with crossed polars. In the cavity filling, groups of oriented Nsuta MnO_2 grains that extinguish at this position alternate with similar groups, differently oriented, which are bright. The general structure appears to be that of slightly mis-oriented sectors of spherulites.

FIG. 19. Polished surface of replacement ore. Plain light, × 10. Quartz-mica-garnet rock partly replaced by lithiophorite and Nsuta MnO_2 and cut by a banded veinlet (upper left) of Nsuta MnO_2 (light gray) and cryptomelane (medium gray). In crumpled zone at left, darker bands are laminae partly replaced by lithiophorite; lighter bands are partly replaced by Nsuta MnO_2. Microscopic textural features indicate that lithiophorite has replaced earlier Nsuta MnO_2 in the bands now rich in lithiophorite. No mineralogical or structural control of lithiophorite is evident.

is shown in some veinlets, particularly those consisting of pyrolusite (Fig. 6), of lithiophorite, or of combinations of the two minerals. Some samples show several periods of fracturing and veining by various manganese oxides (Fig. 7). In many samples, cavity filling has been accompanied by partial replacement of the walls of fractures or of fragments of replacement ore. The result is rounding of fragments of the original rock that are encased in colloform crusts of manganese oxide minerals. In most specimens the colloform crusts are composed entirely of oxides, so that any replacement of rock fragments has been a mass replacement. In a few cases, however, rhythmic alternation of Nsuta MnO_2 and cryptomelane has been produced within the rock fragments (Fig. 8). Such textures are interpreted as diffusion banding.

At the risk of begging the question of processes and stages of ore mineral deposition, it may be stated that the textures and structures of the assemblage are those which would be expected in an ore formed by 1) weathering of manganiferous rocks and residual concentration of part of the manganese as oxides, 2) downward migration of the remainder of the manganese, and 3) reprecipitation of migrating manganese both by replacement of underlying rocks and by healing of fractures produced by progressive slumping.

Certain ore samples cannot be ascribed with assurance either to cavity filling or to replacement. Leaching of impurities and alteration of garnet or other manganiferous minerals to the oxides would produce the textures observed.

MINERALOGY OF THE ORES

General Statement.—The principal oxide constituents of the ores, in order of decreasing abundance, are oxides here designated as Nsuta MnO_2, cryptomelane, pyrolusite, goethite, and lithiophorite. Nsuta MnO_2 comprises natural oxides giving one of three X-ray patterns of the general gamma-MnO_2 type. These patterns are discussed in a subsequent section. As noted above, chief impurities are muscovite, quartz, and garnet. Zircon and amphibole have also been identified. Clay minerals may be present in a few specimens, but no systematic study of these could be attempted with the material available.

Nsuta MnO_2.—Nsuta MnO_2 is the most abundant oxide component of the ores studied. It occurs in all three types of ore discussed above. Nsuta MnO_2 formed by replacement ranges from cryptocrystalline material, nearly isotropic, to finely crystalline and apparently platy masses. It forms platy aggregates along cleavages of muscovite grains (Fig. 1), evidently replacing primary minerals, and pseudomorphs after garnet (Fig. 3) that have a felted appearance under crossed polars. The pseudomorphs are apparently aggregates of minute, randomly oriented, poorly formed plates, and aggregates of platy crystallites. Although a platy habit seems to be characteristic, it is not possible to be sure that Nsuta MnO_2 always has this habit, for sections of thin plates are indistinguishable from fibers. The coarsest plates range from .01 to .04 mm, but at high magnifications the coarser units are seen to be aggregates of minute crystallites in sub-parallel orientation. The fine-grained character of such aggregates is confirmed by X-ray patterns.

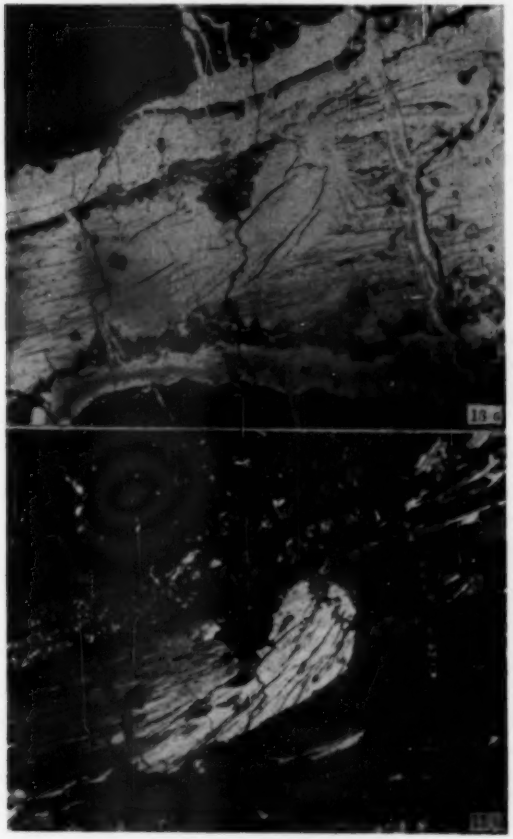


FIG. 13a. Polished surface showing complex oxide veinlet in vein quartz host. Plain light, × 112. Central part of veinlet (white), showing linear structure, is extremely coarse, well-oriented aggregate of Nsuta MnO_2 grains. This material is bordered by thin irregular veinlets of goethite (dark gray), which in turn are flanked by coarse pyrolusite layers (white). The pyrolusite layer at bottom of photograph is cut by a median veinlet of fine-grained mosaic Nsuta MnO_2 (light gray). Complex veinlets of pyrolusite and Nsuta MnO_2 cut across the main veinlet (near right and left sides) and also fill fractures in quartz host (black).

FIG. 13b. Same field as in Figure 14a but photographed with crossed polars. Note strong preferred orientation of the Nsuta MnO_2 at the center of the veinlet. Subsidiary veinlets of pyrolusite and fine-grained mosaic Nsuta MnO_2 border and cut the main veinlet.

Nsuta MnO_2 is also found replacing the other manganese oxides along fractures (Fig. 9), along colloform banding, or diffusely, in the last case appearing in the early stages of replacement as pin-points scattered through other oxides, cryptomelane especially. One sample consists largely of granular pyrolusite in an advanced stage of replacement by Nsuta MnO_2.

In fracture fillings, Nsuta MnO_2 is commonly in very dense, regular layers that alternate with cryptomelane and pyrolusite (Figs. 1, 10, 11). The platy habit previously described is prominent. The plates range from less .001 mm to .04 mm in diameter, but are coarser, on the average, than the plates in replacement ore. Grains are generally of uniform size in a single layer, but adjacent layers differ greatly in grain size, so that banding is easily visible between crossed polars. In many specimens, the coarsest Nsuta MnO_2 is at the centers of symmetrically banded veinlets (Fig. 6). The platelike grains appear to be aggregates of radially oriented crystallites, much like those in replacement ore. The gross pattern of grain aggregates, however, is commonly decussate.

In breccia ore and other cavity fillings, the degree of orientation of crystallites and grain aggregates of Nsuta MnO_2 varies greatly. In some specimens, the central areas of cavity fillings are tightly packed mosaics of polygonal to rounded units, each with near-spherulitic texture. In other specimens, platy grains form dense layers, each of which consists of narrow close-packed but slightly mis-oriented sectors of spherulites (Fig. 12). In several specimens, exceptionally coarse wedge-shaped to platy aggregates of Nsuta MnO_2 are present. These closely resemble crystals of pyrolusite but invariably show the radial extinction characteristic of sectors of spherulites (Fig. 13). In one specimen, layers of Nsuta MnO_2 consisting of partial spherulites up to 0.7 mm in diameter alternate with thin layers consisting of the usual platy aggregates (Fig. 14).

Layering in Nsuta MnO_2 that cements ore fragments or rock fragments is commonly as intricate as that of the simple fracture fillings, but symmetrically banded Nsuta MnO_2 is less well developed (Fig. 11). An interesting feature of botryoidal layers of this type of ore, found to a lesser extent in veinlets and but rarely in replacement type ore, is a pattern of minute transverse cracks that cut fine-grained layers of Nsuta MnO_2 (Figs. 5, 10). Adjacent layers of fine grained pyrolusite or cryptomelane are generally not penetrated. The cracks strongly suggest those commonly ascribed to the dehydration and shrinkage of gels, but their occurrence only in layers of Nsuta MnO_2 remains to be explained.

Another feature characteristic of oxides filling open spaces is the sharp definition of the individual layers (Fig. 1, 11). There is no evidence that layers are the result of successive replacements. In contrast, the contact between the outermost layer and the host rock, which is generally replaced to a large extent by oxides, is irregular and gradational (Fig. 10). It is of considerable interest that Nsuta MnO_2 is abundant in the replaced rock and also commonly forms one or more of the layers in the cavity fillings.

Cryptomelane.—Cryptomelane is an abundant constituent of many of the ore specimens studied, particularly those formed by cavity filling. It is

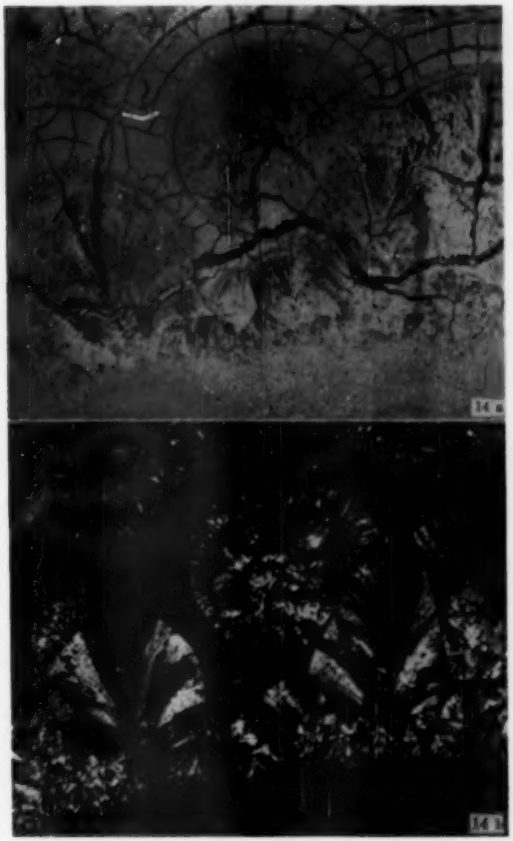


FIG. 14a. Polished surface of colloform cavity-filling ore. Plain light, × 55. Round forms across center of photograph have central areas made up of radiating aggregates of Nsuta MnO_2. Outward and upward are shells of cryptomelane (gray, thin), Nsuta MnO_2 (light gray to white, with transverse cracks), pyrolusite (white, poor polish) and more Nsuta MnO_2. Entire layer of rounded forms rests on a thin layer of mosaic-textured Nsuta MnO_2 that overlies a massive layer of fine-grained pyrolusite (bottom). An irregular veinlet of pyrolusite cuts the round forms from east to west just below center.

FIG. 14b. Same field as Figure 13a photographed with crossed polars. Note plumose Nsuta MnO_2 at center of round forms. Cryptomelane bands appear isotropic (black), and shells of Nsuta MnO_2 and pyrolusite can be distinguished easily; the pyrolusite shell (near top) is relatively coarse. Bright band just below the spherulitic forms is coarse mosaic Nsuta MnO_2.

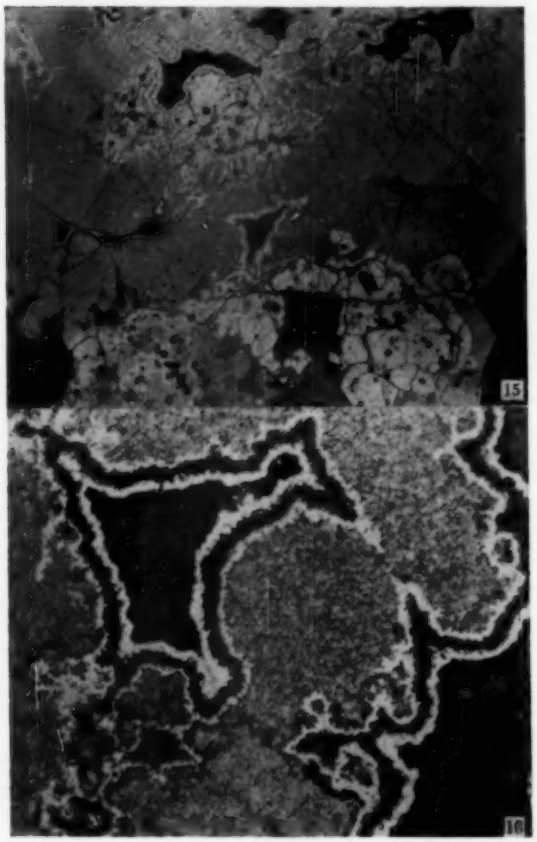


FIG. 15. Polished surface showing colloform cavity ore encrusting replacement ore. Plain light, × 4. Replacement ore (lower third) is partly cryptomelane (gray), partly Nsuta MnO_2 (white). Voids and non-opaque minerals are black. Upper two-thirds—massive cryptomelane (gray), intricately interlayered with Nsuta MnO_2 (white) around cavities. A few cavities are lined with needle-like crystals of cryptomelane.

FIG. 16. Polished surface of complex cavity-filling ore. Plain light, × 200. Coarse-grained lithiophorite in cavities (dark gray) shows comb structure in part (right). Lithiophorite is bordered, progressing outward, by a thin layer of Nsuta MnO_2, a thin lithiophorite layer, a second thin Nsuta MnO_2 layer, and finally a massive replacement intergrowth of lithiophorite and cryptomelane. Cavity-filling and replacement by lithiophorite were evidently contemporaneous and followed deposition of the other oxides.

typically in continuous colloform layers concentric with, and locally alternating with, Nsuta MnO_2 or pyrolusite layers (Figs. 1, 11, 15). In replacement ore, only minor amounts of cryptomelane are generally associated with Nsuta MnO_2, but in one specimen cryptomelane has replaced much of a mica-quartz rock. Veinlike Nsuta MnO_2 cuts the cryptomelane.

Cryptomelane is commonly cryptocrystalline but locally forms discrete needle-like crystals. These may be haphazardly oriented, arranged in radiating groups, or sub-parallel and oriented normal to the surfaces of cavities. Intricate intergrowths of Nsuta MnO_2 plates and cryptomelane needles appear to be present in certain specimens, but distinction of the two minerals in mixtures is not always easy by optical methods. Maximum crystal size measured is 0.15 mm. In some specimens, cryptomelane layers equal layers of the other minerals in thickness, but commonly cryptomelane is present only as one or several very thin layers separating thick layers of other oxides (Figs. 10, 11).

Pyrolusite.—Pyrolusite shows a greater range of grain size than the other manganese oxide minerals in the specimens studied, from .003 mm or less to several millimeters in length. Except in rare cryptocrystalline bands, pyrolusite can be identified readily by optical methods. It is uncommon in replacement ore but fairly abundant in cavity fillings. Veinlets with central areas of pyrolusite showing comb structure are found in many samples (Fig. 6), and cavities lined with stubby prisms of pyrolusite are common.

One specimen shows a matrix of fine-grained mosaic pyrolusite traversed by several veinlets of coarse-grained pyrolusite. The mosaic pyrolusite appears to have formed by replacement of a pre-existing material, the nature of which, however, is not indicated.

Lithiophorite.—Lithiophorite is the least abundant of the manganese oxide minerals; it has been found in only 5 of 38 specimens of ore studied in detail under the microscope. It forms an estimated 20 percent of the polished surface of one specimen, but the complete collection of material suggests that it forms less than 1 percent of the ore on the average.

Lithiophorite commonly occurs in veinlets along fractures or as crusts lining cavities (Fig. 9). The wider veinlets or cavity fillings are symmetrically banded and have typical comb-structure (Fig. 16). Crusts or layers are composed of tabular crystals, poorly oriented aggregates, or close-packed partial spherulites of lithiophorite flakes. Individual grains range from less than a micron to 0.1 mm in length. Where lithiophorite has filled open spaces, mammillary and botryoidal forms are commonly developed, like those commonly found in colloidal precipitates, but the crusts show no internal banding (Fig. 17). In contrast, associated colloform cryptomelane and goethite show fine-scale layering.

Some veinlets have obviously been formed (unmatched walls, enlargement of intersections, gradational contacts) at least partly by replacement of cryptomelane or Nsuta MnO_2 (Fig. 9). In one specimen, replacement of cryptomelane adjacent to lithiophorite-filled fractures has developed intimate intergrowths of the two minerals (Fig. 16). A few veinlets of lithiophorite are actually pseudomorphs of original veinlets of Nsuta MnO_2 or pyrolusite.

Lithiophorite is also found as partial or complete pseudomorphs after garnet in several specimens of quartz-garnet rocks (Fig. 18). In one specimen of quartz-muscovite rock lithiophorite is distributed in many bands that are .03 to .25 mm in width and fractions of a millimeter apart (Fig. 19). The rock was earlier diffusely replaced by Nsuta MnO_2. In the lithiophorite-

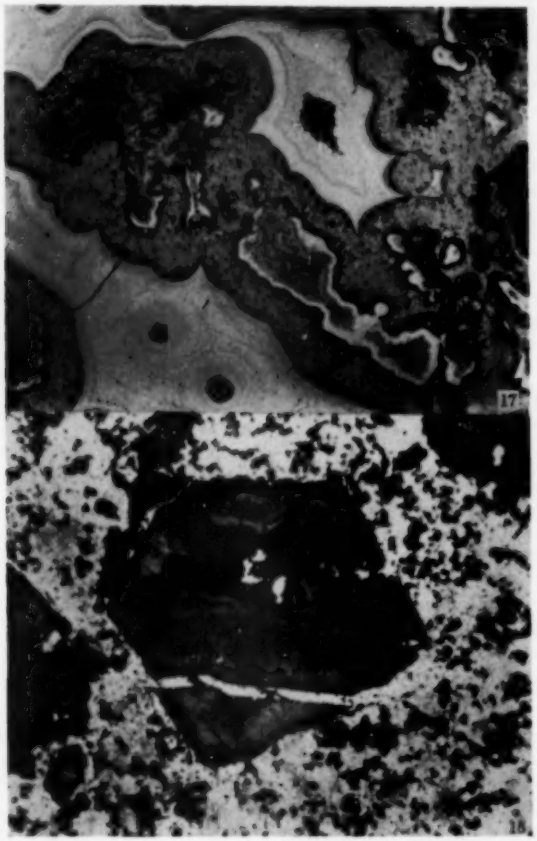


FIG. 17. Polished surface of cavity-filling ore. Plain light, × 50. Lithiophorite (medium gray, massive) surrounds delicately layered iron oxide masses (dark gray), and in turn is bordered by thick-layered cryptomelane (light gray). Note lack of banding in lithiophorite, and needle-like crystals of cryptomelane lining cavity just above center.

FIG. 18. Polished surface of replacement ore. Plain light, × 170. Garnet crystal in center has been almost completely replaced by lithiophorite (medium gray) and goethite (dark gray). Matrix is a quartz-mica rock largely replaced by Nsuta MnO_2 (white), a veinlet of which cuts the replaced garnet. In the matrix dark gray areas are non-opaque minerals.

rich bands, lithiophorite has replaced Nsuta MnO_2, but quartz and muscovite are unaltered. The bands are controlled neither by fractures nor by rock cleavage or bedding, hence probably are an imperfect form of Liesegang rings.

A fine-grained mineral forming most of one specimen of "wad ore" gives a diffuse X-ray pattern somewhat similar to that of lithiophorite, but microscopically the material is in no way like lithiophorite. No published pattern matches the pattern of this material exactly, and its identity remains uncertain.

Distinction of the Manganese Oxide Minerals in Polished Surfaces.—The distinction of Nsuta MnO_2, cryptomelane, pyrolusite, and lithiophorite in properly polished surfaces becomes relatively easy after the observer has acquired some experience with the minerals. Lithiophorite is readily recognizable. It has distinct bireflectance in air (E, medium gray, O, light gray; $R_E = 10.5$ percent, $R_O = 19.5$ percent by the Folinsbee method, in white light), strong anisotropism, polarization colors shades of gray; $A_r = 11.7°$ in air (589 mμ);[1] elongation positive. Dispersion is negligible. Under crossed polars, if the sensitive tint plate is inserted in the system, grains of lithiophorite cut parallel or nearly parallel to the C-axis change from clear blue to clear yellow as the stage is rotated.

Pyrolusite almost invariably occurs in grains that polarize as units. Bireflectance is distinct ($R_E = 33$ percent, $R_O = 39$ percent); the sign of the phase difference is positive; the reaction to the sensitive tint is weak; elongation is positive; $A_r = 4.0°$ (589 mμ); dispersion is distinct, $r > v$; polarization colors are brownish cream, brown, slate gray. Nsuta MnO_2 has faint but distinct bireflectance in air (shades of pale gray); the reflectivity of aggregates ranges from 32.5 percent to 38 percent in air. Aggregates of Nsuta MnO_2 therefore appear slightly grayer than pyrolusite crystals at their position of higher reflectivity, and also are commonly grayer than fine-grained pyrolusite aggregates. Further than this, however, the textures of aggregates of Nsuta MnO_2 in the ores studied serve to distinguish the mineral from pyrolusite. The validity of this criterion has been checked by repeated X-ray determinations. In the rare coarse fibrous or spherulitic aggregates of Nsuta MnO_2, elongation of fibers or sheaves is positive; the effect on the sensitive tint is weak; $A_r = 4.2°$ (589 mμ); dispersion is negligible.

Cryptomelane in Nsuta ores is very finely crystalline; the most useful optical property is reflectivity. For aggregates, $R = 29.5$ percent in white light. Cryptomelane is therefore slightly but distinctly grayer than both pyrolusite and Nsuta MnO_2. Since all specimens containing cryptomelane also contain Nsuta MnO_2, the recognition of cryptomelane is commonly easy, except in uncommon layers that are fine-grained mixtures of the two minerals. The contrast is weakest in perfectly polished specimens but is markedly stronger in the usual polished surface, in which both Nsuta MnO_2 and cryptomelane are apt to be pitted on an extremely minute scale. Because most surfaces of manganese oxides show minute imperfections, measurements of reflectivity have limited value, but relative reflectivities, which remain constant

[1] For discussion of A_r and other rotation properties, see Cameron, E. N., Econ. Geol., vol. 52, p. 252–268, 1957. Values given are corrected values.

despite imperfections, are extremely useful and reliable. The resulting color contrast is emphasized under oil immersion at low magnifications.

Iron oxides in general are readily distinguishable from the manganese oxide minerals, even in fine intergrowths, by their brown, red, or yellow internal reflections, low reflectivity, and weak anisotropism.

Goethite.—Iron oxide is irregularly distributed in the ore specimens studied and is lacking entirely in many. It occurs as colloform-banded fragments cemented by manganese oxides, as veinlets cutting manganese oxides, and intermingled on a minute scale with Nsuta MnO_2 in some specimens of replacement ore. It is invariably extremely fine-grained, and some of it appears from X-ray diffraction patterns to be essentially amorphous.

Samples of iron oxide that gave diffraction patterns at all proved to be goethite, and this name is therefore used as a general term for iron oxide in the present report.

PARAGENETIC SEQUENCE AND STAGES OF FORMATION

Time relations among minerals are clearly indicated in most of the specimens, by veinlets of one mineral cutting others, by pseudomorphs, and by sequences of layers in cavity fillings. It is evident from these relationships that there is no fixed paragenetic sequence of the manganese oxides. Veinlets of any one manganese oxide can be found cutting any of the others. Cryptomelane, pyrolusite, Nsuta MnO_2, and a little lithiophorite occur in alternate layers. Unmatched walls of veinlets and enlargement of intersections indicate that in places earlier-formed oxides have been partly replaced by other oxides.

A broad sequence of oxides, nonetheless, can be recognized despite the numerous variations and exceptions. The sequence is best illustrated in specimens that have developed by a combination of replacement and cavity filling and consist of fragments of rock partly to almost completely replaced by manganese oxides and then cemented by oxides deposited in intervening spaces. In such specimens, the following general sequence is repeatedly shown:

1. Replacement of rock fragments by Nsuta MnO_2.
2. Partial replacement of Nsuta MnO_2 by cryptomelane (in a few specimens).
3. Filling of interstitial spaces.
   a. Deposition of cryptomelane and Nsuta MnO_2, commonly in alternating layers.
   b. Deposition of pyrolusite.
4. Deposition of lithiophorite along fractures or as fillings of cavities left after deposition of the other oxides.

The sequence given above may be regarded as ideal; there are numerous departures. Deposition of the minerals was apparently interrupted and accompanied by fracturing, and the fillings of many of the fractures indicate repetition of a portion of the sequence. In the suite as a whole, it is evident

that every oxide mineral was deposited at several different stages of ore formation. Thus, in one specimen, the earliest mineral to form was pyrolusite, which developed as a mosaic of anhedral crystals by nearly total replacement of rock fragments. Pyrolusite was subsequently replaced in large part by extremely fine-grained Nsuta MnO_2, which pseudomorphs the mosaic texture. In certain other specimens, pyrolusite developed at an intermediate stage of deposition has been fractured and veined by Nsuta MnO_2 and cryptomelane in various combinations. In three specimens, lithiophorite is the last-formed mineral. In a fourth specimen, however, alternating layers of lithiophorite and Nsuta MnO_2 occur, and in a fifth, deposition of lithiophorite was both preceded and followed by deposition of alternating layers of cryptomelane and Nsuta MnO_2.

The processes of ore formation—cavity filling, replacement, and leaching—are quite clear. The alternation of phases and the lack of any consistent sequence seem best explained by variations in the composition and supply of manganese-bearing ground waters migrating downward through the ore. It is evident that each of the three principal MnO_2 minerals of the ore was capable of transformation into any of the others under the conditions existing. Lithiophorite is the only manganese mineral not observed to be replaced by other oxides. Variations in content of alkalies and alumina in the percolating ground waters could explain alterations of Nsuta MnO_2, cryptomelane, and lithiophorite; but factors controlling the stability of Nsuta MnO_2, cryptomelane, and pyrolusite relative to one another are not indicated. Nsuta MnO_2 and cryptomelane appear to have been deposited largely from gels, but pyrolusite and lithiophorite were probably deposited directly as crystals.

The repeated fracturing indicated in almost every sample of ore could well be due to slumping of the material with progress of weathering and enrichment.

Lithiophorite has been discussed so little in the literature that comparison with other known occurrences is desirable here. In the Postmasburg District, Union of South Africa, de Villiers (5) found lithiophorite 1) disseminated sparingly in bixbyite, 2) as coarsely crystalline aggregates associated with braunite, bixbyite, hematite, psilomelane, and diaspore, and 3) as finely crystalline, thin layers in laminated psilomelane-hematite ore. From his description, it seems evident that the coarsely crystalline aggregates occur as crusts on bixbyite, hence that lithiophorite, in part at least, is later in the sequence. Beyond this, the time relations are not indicated. At Buchan, Australia, Samson and Wadsley (22) reported lithiophorite intimately associated with chalcophanite.

Neither of the above occurrences shows much in common with the mineralogical association of Gold Coast ore. At the Merid mine, Lafaiete, Minas Gerais, Brazil, however, Horen (11) has described lithiophorite in association with other manganese oxides. In the silicate-carbonate protores, it is found rimming partly decomposed garnets, and Horen concluded that lithiophorite represents a transitional stage in the breakdown and alteration of garnets to MnO_2 minerals plus aluminous clays. Lithiophorite and lithian wads were

also found among the supergene minerals filling fractures in the ore and protore.

The occurrence of lithiophorite as given by Horen bears a general resemblance to the occurrence of the mineral in Nsuta ores. In both it occurs as a replacement of garnet. In Nsuta ore, however, where lithiophorite is associated with other manganese oxides in pseudomorphs after garnet, and where time relations can be determined, lithiophorite is later than other Mn oxides. This is in agreement with its general position in the paragenetic sequence as shown by the cavity fillings. It does not appear to be a transitional product in the alteration of garnet at Nsuta.

X-RAY DIFFRACTION STUDIES

General.—The X-ray studies of ore samples from Nsuta were performed primarily to identify fine-grained minerals and to check identifications made microscopically. The micro-samples described earlier were X-rayed using Norelco Straumanis-type powder cameras with a radius of 28.65 mm. Patterns obtained were measured by means of the N. P. Nies transparent template, and intensities were estimated visually. Certain samples of Nsuta MnO_2 were also exposed in cameras with a 57.3 mm radius to permit more accurate pattern measurement. The *d* spacings of lines on the larger films were measured using a Norelco millimeter scale reading directly to 0.1 mm, and relative intensities were checked by means of a Hilger and Watts photoelectric densitometer. A Norelco basic X-ray unit was used to provide Fe radiation filtered with MnO_2.

Standard Patterns.—X-ray powder patterns of most of the manganese oxide ore minerals have been listed and discussed by Fleischer and Richmond (8) and Ramdohr (21). These investigators did not describe Nsuta MnO_2 or other material of the gamma-MnO_2 type. Gamma-MnO_2 has been discussed by numerous authors (23, 18, 19, 3, 2, 4, and 28), however, since it was first named by Glemser (9).

Cryptomelane, pyrolusite, and lithiophorite.—Cryptomelane, pyrolusite, and lithiophorite give distinctive powder patterns, as shown by the close agreement of patterns of these minerals obtained by different investigators. The *d* spacings may vary slightly depending upon the exact chemical composition of given specimens, but identification of these minerals by X-ray methods in relatively pure samples is not difficult, as a rule. Typical patterns of these minerals in the Nsuta ore are given in Table 1 together with published patterns.

Nsuta MnO_2.—Systematic identification of Nsuta MnO_2 and material of the gamma-MnO_2 type is difficult for several reasons. First, the patterns obtained from this material vary from specimen to specimen in clarity, completeness, and interplanar spacings. The lines are commonly somewhat diffuse, and contrast is poor because of background fogging; reproducible measurements are therefore difficult. Second, the nomenclature developed by various workers for similar material is based upon the study of artificial products as well as ores, most of which give somewhat different X-ray pat-

terns, and a usable terminology has not yet been agreed upon. Third, patterns made by use of different apparatus, such as the diffractometer and the powder camera, and patterns of materials of unknown purity add apparent discrepancies to the numerous real differences in X-ray patterns. To avoid contributing to further confusion, the authors propose to use previously defined terms as rigorously as possible.

TABLE 1

Pyrolusite				Cryptomelane				Lithiophorite			
I[a]		II[b]		III[c]		IV[d]		V[e]		VI[f]	
I/I$_0$	*d* (A.)	*d* (A.)	I/I$_0$	I/I$_0$	*d* (A.)	*d* (A.)	I/I$_0$	I/I$_0$	*d* (A.)	*d* (A.)	I/I$_0$
W	3.43	3.48	10	9	6.863	6.9	10	9	9.407	9.4	5
VS	3.13	3.14	100	8	4.892	4.9	7	1	5.13	5.2*	1
S	2.41	2.41	50	3	3.445	3.45	0.5	10	4.70	4.73	10
W	2.20	2.21	10	10	3.105	3.13	9B	3	3.13	3.15	3
M	2.12	2.13	25	3	2.445			1	2.48	2.49	1
M	1.97	1.98	15	7	2.387	2.40	10			2.41	3
		1.81	5	1	2.305			9	2.35	2.36	5
		1.68	?	4	2.183			1	2.27	2.27	1
VS	1.62	1.63	50	5	2.145	2.14	4	1	2.12	2.15	1
S	1.56	1.56	25	1	2.097			1	2.04	2.03	1
W	1.44	1.43	15	1	1.961	1.95	0.5B	8	1.87	1.88	5
W	1.39	1.40	15	2	1.917					1.65	0.5
S	1.31	1.31	20	5	1.820	1.82	2	6	1.55	1.58	3
VW	1.25			4	1.633	1.63	1B			1.47	2
VW	1.20	1.20	5	4	1.618					1.45	2
VW	1.16			1	1.544	1.54	3	7	1.44		
VW	1.12	1.125	5	6	1.528					1.43	1
VW	1.10			2	1.423	1.43	3			1.40	1
M	1.05	1.057	15	0.5	1.385			5	1.38	1.37	1
W	1.04	1.04	10			1.36	2B			1.24	0.5
W	1.00	1.0	10	5	1.347			6	1.23	1.23	1
						1.30	1	2	1.18	1.18	0.5B
				1	1.289			2	1.14	1.14	0.5B
				0.5	1.230					1.07	0.5B
				0.5	1.209						
				0.5	1.190						
				0.5	1.135						
				1	1.073						
				1	1.052						

* Line possibly due to K-beta radiation.
[a] Ramdohr, 21, p. 48–49.
[b] Univ. of Wis., Spec. No. A115 (Nsuta).
[c] Fleischer and Richmond, 8, p. 280.
[d] Univ. of Wis., Spec. No. A97 (Nsuta).
[e] Fleischer and Richmond, 8, p. 282.
[f] Univ. of Wis., Spec. No. A34–1 (Nsuta).

The term gamma-MnO_2, as first used by Glemser, referred to an artificial manganese dioxide with an X-ray pattern consisting of eight lines, one of them questionable, as shown in Table 2.

Cole, Wadsley, and Walkley (3) compared Glemser's pattern with similar patterns published by Dubois (6), McMurdie (18), and patterns obtained

TABLE 2

GAMMA-MnO_2 POWDER PATTERNS

Glemser (9)		Cole et al. (3)	
d (A.)	I/I_0	I/I_0	d (A.)
3.89	M[a]	S (d)	4.02
		VVW	2.53
2.42	M	M	2.41
2.09	M	MS	2.10
1.80	?		
1.614	VW	VS	1.62
1.416	VW		
		W	1.38
1.349	VW		
1.305	VW		
		VVW	1.25

[a] In the tables, the symbols are as follows: VS—very strong, S—strong, MS—medium strong, M—medium, W—weak, VW—very weak, VVW—very, very weak; (d)—diffuse.

during their own research. They concluded that the term gamma-MnO_2 should be used for material giving simple patterns similar to that of Glemser's original material (Table 2), but not necessarily exactly like his pattern. Small differences in recorded d measurements may be due to minor structural differences in the specimens and to difficulties inherent in accurately measuring weak or broad lines. In addition, they recognized more complex patterns, termed types I and II gamma-MnO_2 (Table 3), which they considered additional discrete modifications of MnO_2.

The lines that distinguish these patterns from Glemser's gamma-MnO_2 are at 2.33 A., 2.57 A., and 1.37 A. in Type I, and at 4.38 A., 2.68 A., 2.34 A., 2.05 A., and 1.59 A., in Type II. The line at 3.10 A. in the Type II pattern was said to be due to pyrolusite as a minor constituent.

Others workers have also noted differences in patterns of gamma-MnO_2 type material, as mentioned by Cole et al., in both artificial products and ores. Schossberger (23) reportedly identified material of the gamma-MnO_2 type as well as pyrolusite in West African ores, and noted that a series of different patterns, perhaps transitional to pyrolusite, was observed. Feitknecht and Marti (7) showed diagrams of 3 types of patterns obtained from artificial products. Two of their patterns, type a and type b, appear to be similar to

TABLE 3

Gamma-MnO_2 I		Gamma-MnO_2 II	
d (A.)	I/I_0	I/I_0	d (A.)
		M	4.38
3.94	S	MS	3.82
		W	3.10 (impurity)
2.57	W	W	2.68
2.41	M	MS	2.42
2.33	VW	W	2.34
2.11	MS	S	2.12
		W	2.05
1.62	VS	S	1.63
		W	1.59
1.41	VW	VW	1.43
1.37	VW	VW	1.35
		VW	1.31

the gamma-MnO_2 and gamma-MnO_2^I of Cole et al., as noted in the later paper. The third pattern, unnamed, is more complex than the others and appears to be similar to gamma-MnO_2^{II}, except for the absence of the line at 4.38 A. Cole et al. did not note this resemblance, however. Unfortunately, Feitknecht and Marti did not tabulate the *d* spacings of the lines in their patterns and did not provide a scale for measurement; the tabulated patterns of Cole et al., are, therefore, to be preferred for reference purposes.

The distinctions made by Cole et al., have been criticized by others, however, including Levin (17), Tauber (27), McMurdie and Golovato (19), and Delano (4), who maintained that an infinite variety of closely similar patterns of gamma-MnO_2 type exists and that introduction of new terms is unwarranted. It is noteworthy, however, that Cole and his co-workers identified Type I gamma-MnO_2 in certain ore samples and as the major constituent in some samples of Gold Coast (Ghana) ore, indicating that this variety may, indeed, be a unique naturally occurring material. Gamma-MnO_2^{II} was not found in the ores studied by these men.

Since the first use of the term gamma-MnO_2^I for naturally occurring material, the term has not appeared in the literature, as far as is known to the writers. Various authors have noted abundant gamma-MnO_2 in the Nsuta ores (23, 18, 19, 28, 4, 26) and have given patterns containing from 4 lines (19) to 18 lines (10), but the distinction between gamma-MnO_2 as described by Glemser and material giving a similar but much more complex X-ray pattern evidently was not considered significant until 1955 or later. In 1958, William F. Nye (20) wrote that the dominant mineral phase of Gold Coast ore gave an X-ray pattern identical to a chemically prepared MnO_2 termed *rho* (Signal Corps, U. S. Army, 25). Nye remarked that rho-MnO_2 is clearly different from gamma-MnO_2.

In the present investigation, it was decided to designate as Nsuta MnO_2 the oxides of the Nsuta deposit that give X-ray powder patterns generally similar to those of gamma-MnO_2 as given by earlier workers, and to reserve the terms gamma-MnO_2 and rho-MnO_2 for artificial products. The latter terms are thus used as originally defined, and recognition is given to the fact that Nsuta MnO_2 is a mineral or a mineral group. Furthermore, certain differences are apparent in the patterns of the artificial and natural compounds, and misleading or inaccurate comparisons may be avoided by strict adherence to the suggested terminology.

In order to systematize identification of the Nsuta MnO_2 in the specimens studied, the powder patterns of more than fifty samples were carefully compared. It was found that all the patterns were basically similar with respect to relative sharpness and general distribution of the lines, but that the patterns fell into three groups according to *d* spacings and relative intensities of the lines. The best pattern of each group was selected and used for a standard. For practical purposes, these three patterns are referred to henceforth as Type 1.64, Type 1.65, and Type 1.67, the number referring to the *d* spacing of the line near 1.65 A. This line is used as a reference because of the relative ease of measuring with accuracy the *d* values in this region on film. The

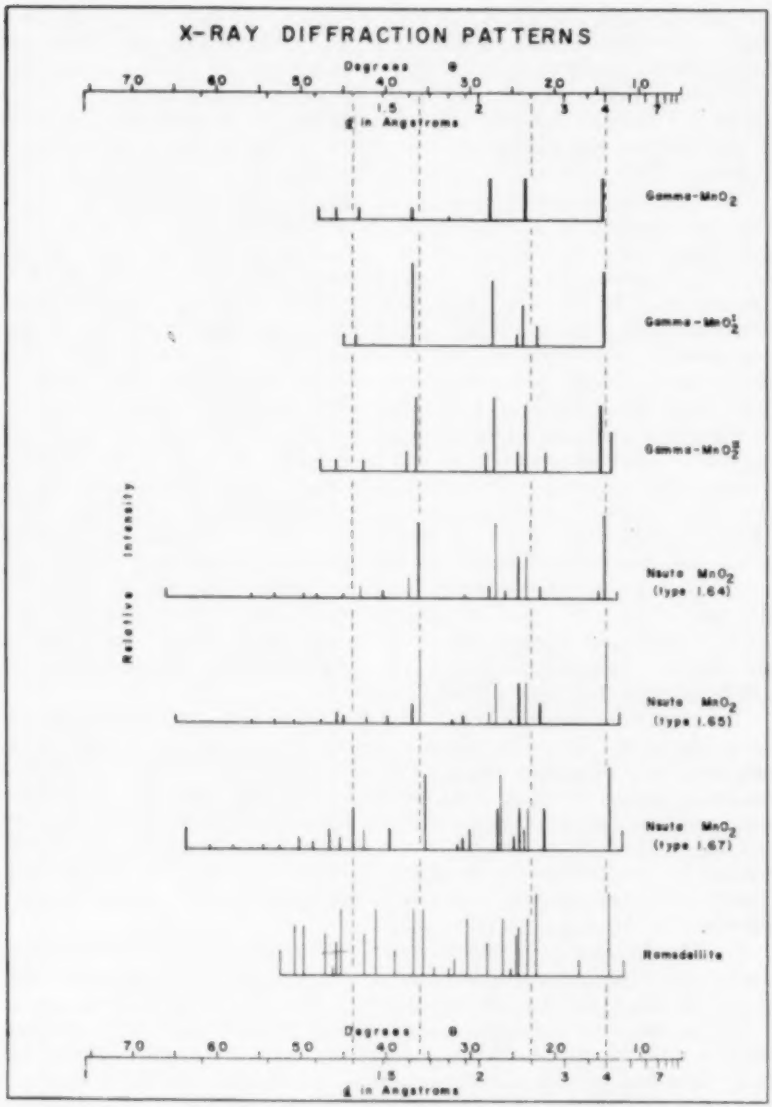


FIG. 20. X-ray diffraction patterns obtained with FeK-alpha radiation. Sources: Gamma MnO_2: Glemser (9); Gamma MnO_2^{I}: Cole et al. (3); Gamma MnO_2^{II}: Cole et al. (3); Nsuta MnO_2 (type 1.64); Univ. of Wis. Spec. No. A-149; Nsuta MnO_2 (type 1.65): Univ. of Wis. Spec. No. A-73; Nsuta MnO_2 (type 1.67): Univ. of Wis. Spec. No. A-69; Ramsdellite: ASTM card 7-222. Different line widths indicate differences in line sharpness on x-ray films.

TABLE 4

Nsuta MnO_2[a] (type 1.64)		Nsuta MnO_2[a] (type 1.65)		Rho-MnO_2[a] [b]		Ramsdellite[c]			Nsuta MnO_2[a] (type 1.67)	
I/I_0	d (A.)	I/I_0	d (A.)	I/I_0	d (A.)	I/I_0	d (A.)	hkl	I/I_0	d (A.)
VVW	4.4	VW	4.45			20	4.64	020	W	4.58
VS	3.96	VS(s)	4.00	10(d)	4.0	100	4.07	110	VS	4.11
VVW	3.75									
						20	3.24	120		
									M	2.66
VW	2.60	W	2.59	2(vb)	2.60	100	2.55	130		
									M	2.46
M(s)	2.43	M(s)	2.43	9(s)	2.43	70	2.44	021		
									W(s)	2.41
M	2.34	M	2.35	4	2.35	60	2.34	111	M	2.36
						50	2.32	040		
VVW	2.21	Tr	2.25			10	2.27	200	VW	2.29
						70	2.19	121	S(s)	2.17
S(s)	2.13	M(s)	2.13	10	2.12				M	2.14
VW	2.07	VW(s)	2.07			40	2.06	140		
									W	1.93
Tr	1.90	VVW	1.89			70	1.91	131	VW	1.88
		Tr	1.82			20	1.83	230	Tr	1.85
						10	1.80	041		
						10	1.72	150		
S	1.64	S(s)	1.65	8	1.65	80	1.66	221	S	1.67
W(s)	1.60	W	1.61			80	1.62	240		
VVW	1.50	VVW	1.51			30	1.54	231	W	1.52
						80	1.47	151		
VW(s)	1.42	VVW(s)	1.44	8(s)	1.43	50	1.43	002	W(s)	1.43
									M	1.40
Tr	1.37	VVW	1.37	2	1.36	80	1.36	061	VW	1.36
		VW	1.35			40	1.35	112		
						10	1.34	301	W	1.33
Tr	1.30	Tr	1.31	2(vb)	1.30	50	1.32	311	VVW	1.29
Tr	1.27					60	1.27	170	VW	1.26
		Tr	1.25	vw	1.25	60	1.25	132		
Tr	1.21	?	1.21	vw	1.21	30	1.22	042	Tr	1.22
Tr	1.17	Tr	1.17						Tr	1.19
									Tr	1.14
									Tr	1.11
VVW	1.06	VVW	1.07	2(vb)	1.07				W	1.08

[a] Lines are broad unless designated sharp by letter s or very broad by letter vb.
[b] Signal Corps, U. S. Army (25), revised.
[c] ASTM card No. 7-222 (Bystrom).

patterns are given in Table 4, together with patterns of rho-MnO_2 and the mineral ramsdellite. These patterns are presented graphically in Figures 20 and 21, with patterns of gamma-MnO_2, gamma-MnO_2^I, and gamma-MnO_2^{II}, as well as pyrolusite, for comparison.

Type 1.64, which was found in polished surfaces of 13 different specimens, has a marked similarity to the pattern for gamma-MnO_2^{II} as far as that pattern is given. Type 1.65, found in polished surfaces of 10 different hand specimens, is very similar to Type 1.64, but spacings of a number of the lines are greater than in Type 1.64, and the patterns obtained were generally sharper than those of Type 1.64.

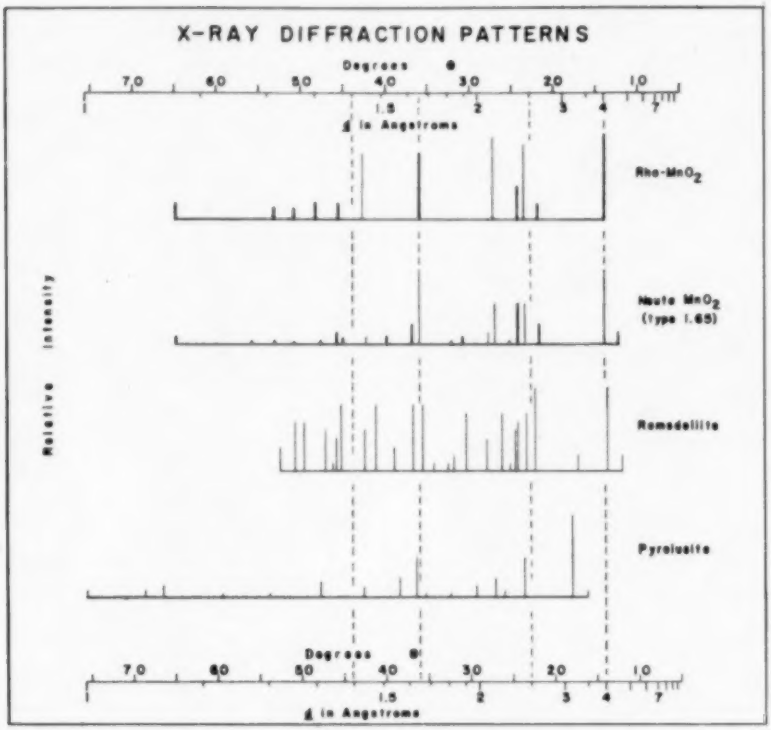


FIG. 21. X-ray diffraction patterns obtained with FeK-alpha radiation. Sources: Rho-MnO_2: Signal Corps, U. S. Army (25), revised; Nsuta MnO_2 (type 1.65): Univ. of Wis. spec. No. A-73; Ramsdellite: ASTM card 7-222 (Bystrom); Pyrolusite: Univ. of Wis. spec. No. A-115. Different line widths indicate differences in line sharpness on x-ray films.

The Type 1.65 pattern strongly resembles the pattern of rho-MnO_2 given by the Signal Corps (25) and revised by Nye (20). Certain lines of the Type 1.65 pattern (at 4.45 A., 2.25 A., 2.07 A., 1.89 A., 1.82 A., 1.61 A., 1.51 A., 1.35 A., 1.17 A.) are lacking in this rho-MnO_2 pattern (Table 4, Fig. 21), but these lines are present in a powder film pattern, said to be of rho-MnO_2, supplied by Mrs. U. B. Marvin. Whether these weak lines were absent or overlooked in the Signal Corps pattern is not known. In any case, further study of the apparently close relation between rho-MnO_2 and Type 1.65 Nsuta MnO_2 should be made.

The Type 1.65 pattern also has a similarity to that of well-crystallized ramsdellite, but certain differences are apparent in *d* spacings and line character. For example, only six lines in the pattern of Type 1.65 are relatively sharp, whereas all of the lines in the ramsdellite pattern are very sharp.

Further, four fairly strong lines indexed as 130, 131, 230, and 041 (Table 4) in the ramsdellite pattern are very weak in Type 1.65, and two other lines, indexed as the 111 and 040 reflections, are represented in Type 1.65 by a broad strong line.

Type 1.67 is an unusual variety in that it was found in polished surfaces of only 3 hand specimens. In overall appearance the pattern is much like Type 1.65 but *d* spacings of all the lines are larger than those of corresponding lines of the other types, and the conspicuous pair of lines near 1.65 A. is replaced by a broad line at 1.67 A. In addition moderately strong lines are present at 2.46, 2.17, and 1.40 A.

A sub-variety of Type 1.64 was found in polished surfaces of 4 of the 13 hand specimens in which Type 1.64 was identified. The pattern is similar to Type 1.64 but is weak and contains only six measurable lines, the strongest of which are at approximately 3.8 A., 2.43 A., and 2.13 A. This material very likely has the same general structure as Type 1.64, but it may be mixed with a large proportion of amorphous manganese dioxide.

Terminology.—In view of the differences in X-ray patterns of the natural and artificial compounds, and the uncertain relations between the materials in question, the use of the term Nsuta MnO_2 for the natural materials seems justified. Thus, the results of the present research may be clearly expressed without danger of implying direct relations, which are really unknown, to artificial compounds. These results suggest that we are dealing with a discrete group of natural materials which, however, differ somewhat in crystal structure, and probably in chemical composition, and that the variations are expressed in stepwise changes in the powder pattern. In support of the view that the materials studied represent one mineral or are members of a mineral group, it is emphasized that each of the many powder patterns obtained is identical to one or the other of the three types cited. Furthermore, a sample from the Quadrilátero Ferrífero, Brazil (collected by J. E. O'Rourke and X-rayed by S. W. Bailey) and one from Busuanga Island, Philippines (collected by R. K. Sorem), gave patterns closely similar to those of the Nsuta material. Samples from other localities will be studied as a means of checking the validity of the proposed group, and it is hoped that other investigators will present X-ray patterns from their files to aid in this phase of the problem. Eventually we hope to gather chemical data and more physical data so that the proposed mineral may be properly characterized.

It is notable that no evidence has been found in the X-ray patterns to support the belief of McMurdie and Golovato (19) that material of the gamma-MnO_2 type, including Nsuta MnO_2, is poorly crystallized pyrolusite, or that an infinite variety of patterns exists transitional from pyrolusite to ramsdellite, as postulated by Bystrom (2) and Delano (4). Patterns of these minerals may be compared with those of the Nsuta MnO_2 group in the tables and the figures. Dissimilarities among the patterns are marked. It is suggested that the inadvertent use of polymineralic specimens in X-ray work could easily lead to the conclusion that a continuous gradation exists from pyrolusite to ramsdellite.

Likewise, the results of the present investigation do not tend to support the view of Cole et al. (3), Tauber (27), and Delano (4), that "Gold Coast gamma-MnO_2" (Nsuta MnO_2) is poorly crystallized ramsdellite. Powder patterns of Nsuta MnO_2 show certain similarities to the pattern of ramsdellite, (see tables and figures), but the differences are striking, particularly in the pattern of Type 1.67, the material that gave the clearest pattern and which, therefore, may be the best-crystallized.

The question naturally arises as to the reasons for the differences in the type patterns of the proposed Nsuta MnO_2 group. Of particular interest are variations in line breadth, discrepancy in number of lines, and minor differences in interplanar spacings. Only preliminary and general suggestions may be made at present, as the crystal structure of the material and the chemical compositions of the specimens are poorly known, but these may be worthwhile. First, actual differences in crystal structure and composition may cause the differences in X-ray patterns. For example, the structure may be imperfect due to minor impurities, order-disorder phenomena, or non-stoichiometric composition. Also, certain types of defects in structure may cause changes in symmetry, or may cause diffraction to occur at angles slightly different from the true Bragg angle θ. Further, the ratio of amorphous MnO_2 to crystalline MnO_2 in different specimens may vary widely. In addition to these internal causes of pattern variations, other factors of a more mechanical nature must be considered. For example, great variations in grain size, preferred orientation of crystals, and different modes of X-ray investigation may lead to presentation of different results from small samples of a single ore specimen. As an illustration, a diffractometer sample is many times larger than that used in the powder camera, and, considering our observations, such larger samples will almost invariably be mineral mixtures. The diffractometer would therefore record lines from two or more minerals, and superposition of some lines could occur. In another instance, the diffractometer record of a pure sample with an X-ray pattern characterized by paired lines only 0.02 or 0.03 A. different in d spacing may not resolve the two lines, particularly if one of the pair is very weak or the pattern background strong.

Possible fundamental differences in crystal structure are clearly of the greater importance in attempts to understand better the nature of Nsuta MnO_2, but the mechanical causes of differences in data must be borne in mind when the work of different investigators is compared. However, until the crystal structure of this modification is known, a full understanding of the cause and of the significance of the variations in powder patterns of the group will not be possible.

SUMMARY

Three types of ore—replacement, cavity-filling, and residual—have been recognized in specimens from Nsuta. Replacement and cavity-filling ores are the most common and are intimately associated in many specimens.

Structurally, the ores are complex and range from massive to well-layered. Layering and other features inherited from the original rocks are cut by

irregular banded veinlets, and colloform layering and botryoidal forms are common. Many textural features such as spherulitic aggregates and pseudomorphic relations are common but visible only under the microscope.

Nsuta MnO_2 and cryptomelane are the most abundant manganese oxides found, but pyrolusite and lithiophorite are common and are abundant in some specimens. In most specimens these minerals can be distinguished from one another by microscope study, but control of the optical work by means of X-ray identification of micro-samples is essential. Where grain size is very small, powder camera X-ray study is the only sure means of identification.

The term Nsuta MnO_2 is introduced as a tentative name for the mineral or mineral group most abundant in the ores. Although Nsuta MnO_2 has physical and optical properties that commonly permit its identification microscopically, it has not been previously described. Earlier investigators have referred to the chief constituent of Nsuta ores as gamma-MnO_2 or rho-MnO_2 on the basis of X-ray examination, but evidently no attempt has been made to study pure samples and precisely characterize the natural material. In the present work, three discrete variants are indicated by X-ray powder patterns, and none gives a pattern identical with published patterns of gamma-MnO_2 or rho-MnO_2.

The general sequence of mineral formation is Nsuta MnO_2 earliest, then cryptomelane, pyrolusite, and lithiophorite. The sequence is not complete in most specimens, and reversals and partial repetition are common.

Oxide formation as a whole was evidently controlled to a large extent by mineralogy of the host rock and fractures, but the factors that determined the oxide phase stable at any particular stage are not known.

The mode of origin of the ores remains problematical, chiefly because of the lack of detailed information on the field geology. The minerals and features of the ores observed in the laboratory, however, are consistent with a supergene origin.

UNIVERSITY OF WISCONSIN,
MADISON, WIS.,
Jan. 8, 1959

REFERENCES

1. Bishopp, D. W., and Hughes, W. J., 1930, A contribution to the geology of the manganese ore-deposits in the Gold Coast Colony and in Ashanti: Inst. Min. Metallurgy Trans., London, v. 39, p. 142–191.
2. Bystrom, Ann Marie, 1949, The crystal structure of ramsdellite, an orthorhombic modification of MnO_2: Acta Chem. Scand., v. 3, p. 163–173.
3. Cole, W. F., Wadsley, A. D., and Walkley, A., 1947, An x-ray diffraction study of manganese dioxide: Electrochem. Soc. Trans., v. 92, p. 133–158.
4. Delano, Philip H., 1950, Classification of manganese dioxides: Industrial and Eng. Chem., v. 42, no. 3, p. 523–527.
5. De Villiers, J. E., 1945, Lithiophorite from the Postmasburg manganese deposits: Am. Mineralogist, v. 30, p. 629–634.
6. Dubois, P., 1936, Contribution to the study of oxides of manganese: Ann. Chim., v. 5, p. 411–482.
7. Feitknecht, W., and Marti, W., 1945, Manganite and artificial manganese dioxide: Helv. Chim. Acta, v. 28, p. 149–156.
8. Fleischer, Michael, and Richmond, W. E., 1943, The manganese minerals: a preliminary report: ECON. GEOL., v. 38, no. 4, p. 269–286.

9. Glemser, Oskar, 1939, A new modification of manganese dioxide: Ber. deut. chem. Ges., v. 72 B, p. 1879–1881.
10. Glicksman, Richard, and Morehouse, C. K., 1956, Resistivity studies of various Leclanche cathode materials: Jour. Electrochem. Soc., v. 103, p. 149–153.
11. Horen, Arthur, 1953, The manganese mineralization at the Merid Mine, Minas Gerais, Brazil: Ph.D. Thesis, Harvard University, unpublished.
12. Junner, N. R., 1931, Nsuta manganese ores: Ann. Rept. Gold Coast Geol. Surv., p. 4–5.
13. ——, 1935, Manganese deposits of Nsuta, Gold Coast: Cong. Intern. des Mines, Met., et Geol. Appl., VIIth Session, Paris, p. 173–178.
14. Kitson, A. E., and Wyllie, B. K. N., 1915, Reconnaissances in the Gold Coast Colony, Ashanti and the Northern Territories: Ann. Rept. Gold Coast Geol. Surv., 1913–1914, p. 6–9.
15. ——, and Wyllie, B. K. N., 1916, Discovery of manganese ore deposits near Tarkwa: Ann. Rept. Gold Coast Geol. Surv., 1915, p. 7–8.
16. ——, 1927, Manganese ore deposits of the Gold Coast, Africa (with notes on the petrology of certain associated manganese silicate-bearing rocks, by N. R. Junner): Am. Inst. Min. Met. Eng. Trans., v. 75, p. 372–395.
17. Levin, S. Benedict, 1947, Discussion, *in* An x-ray diffraction study of manganese dioxide, by Cole et al., 1947: Trans Electrochem. Soc., v. 92, p. 133–158.
18. McMurdie, H. F., 1944, Microscopic and diffraction studies on dry cells and their raw materials: Trans Electrochem. Soc., v. 86, p. 313–326.
19. McMurdie, H. F., and Golovato, E., 1948, A study of the modifications of manganese dioxide: Jour. Research Nat. Bur. Standards, v. 41, p. 589–600.
20. Nye, William F., 1958, Report of the subcommittee on structure and morphology, Battery Grade MnO_2 Committee, U. S. Army Signal Engineering Laboratories: typewritten, unpublished.
21. Ramdohr, Paul, 1956, The manganese ores, *in* Symposium on deposits of manganese: XX Cong. Geol. Intern., Mexico, t. 1, p. 19–73.
22. Samson, H. R., and Wadsley, A. D., 1948, A manganese oxide mineral from Buchan, Victoria: Am. Mineralogist, v. 33, p. 695–702.
23. Schossberger, F., 1940, X-ray examination of natural and synthetic manganese dioxide: Batterien, v. 9, p. 17–20, 33–35 (Abstract in Chem. Abstracts, v. 37, 1316, 1943).
24. Service, H., 1943, The geology of the Nsuta manganese ore deposits: Gold Coast Geol. Surv., Mem. 5, 32 p.
25. Signal Corps Engineering Laboratories, 1955, Specification for manganese dioxide, military battery grade: U. S. Army Signal Research and Devel. Lab., dated July 28, 1955, 18 p., mimeographed, unpublished.
26. Skewes, H. R., Wadsley, A. D., and Walkley, A., 1952, The behaviour of manganese oxides in Leclanche-type dry cells: Austral. Jour. Appl. Sci., v. 3, p. 368–383.
27. Tauber, John A., 1947, Discussion, *in* An x-ray diffraction study of manganese dioxide, by Cole et al.: Trans Electrochem. Soc., v. 92, p. 133–158.
28. Vinal, George W., 1950, Primary batteries: John Wiley and Sons, Inc., New York, 336 p.

Economic Geology
Vol. 55, 1960, pp. 311–326

COMPOSITION AND AGE OF THE TEMISCAMIE IRON-FORMATION, MISTASSINI TERRITORY, QUEBEC, CANADA

TERENCE T. QUIRKE, JR., SAMUEL S. GOLDICH, and HAROLD W. KRUEGER

CONTENTS

	PAGE
Abstract	311
Introduction	312
Regional geology	312
Sam Gunner group	312
Takwa intrusive complex	314
Papaskwasati group	315
Mistassini group	315
Lower and Upper Albanel formations	315
Boulder Bay quartzite	316
Temiscamie iron-formation	316
Kallio slate	316
Coom Lake intrusions	317
Grenville metamorphic complex	317
Structure	318
Composition of the Temiscamie iron-formation	319
Age and correlation	320
Acknowledgments	325
References	325

ABSTRACT

The Temiscamie iron-formation of the Lake Albanel Iron Range in Mistassini Territory, Quebec, is approximately 700 feet thick and is divided into six members on the basis of lithology. The principal iron-bearing minerals are siderite, magnetite, hematite and iron silicates. A bulk chemical analysis of the iron-formation, excluding the thin lower argillite member, shows 29 percent of total Fe and is similar in many respects to the average compositions of iron-formations of the Mesabi, Cuyuna and Gogebic districts.

The Temiscamie iron-formation is overlain by the Kallio slate and is underlain by the Boulder Bay quartzite and the Upper and Lower Albanel dolomites, the sequence constituting the Mistassini group. These rocks are underlain by sediments of the Papaskwasati group, which rest with angular unconformity on a basement of folded sediments and volcanics of the Sam Gunner group. The latter was earlier intruded by igneous rocks of the Takwa complex. The Papaskwasati and Mistassini sediments are relatively unmetamorphosed. They dip to the southeast and abut against high-grade metamorphic and igneous rocks of the Grenville subprovince along the Mistassini fault. The names Boulder Bay quartzite, Sam Gunner group and Takwa complex are introduced.

The Temiscamie iron-formation, on the basis of lithology, has been correlated with the iron-formation of the Labrador trough. Results of radioactivity dating are inconclusive but indicate the possibility of the Temiscamie iron-formation being younger than the Huronian iron-formations of the Lake Superior districts. At the same time the radioactivity dates from northern Quebec and Labrador suggest a complicated geologic history for this region. Effects of the Grenville orogeny have been superimposed on rocks that were involved in two earlier major orogenies.

INTRODUCTION

RECENT exploration of the Temiscamie iron-formation in the region of Lake Albanel, Quebec, has afforded opportunity for the geologic studies that are the basis for the present paper. The Temiscamie is one of several iron-formations which have been investigated by various companies in recent years in the search for direct-shipping ores and others amenable to beneficiation.

The Mistassini district is located approximately 100 miles north of Chibougamau and 400 miles north of Montreal in Mistassini Territory (Fig. 1). The Lake Albanel Iron Range covers 150 to 175 square miles and is included within the area of Figure 2. The regional geology, structure, composition and age of the Temiscamie iron-formation are considered at this time; the detailed stratigraphy and mineralogy will be presented in a subsequent paper (T. T. Q.).

The recent geologic publications on the Mistassini district are by Neilson (17, 18, 20), Neale (15), and Wahl (25). The most comprehensive report on the area is the unpublished doctoral dissertation of Neilson (16). The geologic map of the Lake Albanel Iron Range (Fig. 2) has been compiled from the maps of Neilson, Neale and Wahl, supplemented by data from unpublished company reports and the field work of Quirke.

Since 1952, M. J. O'Brien Ltd., Ottawa, and Canadian Cliffs Ltd., Port Arthur, have been investigating the iron-formation along the east shore of Lake Albanel. In 1955–1956 these companies merged their interests as Albanel Minerals Ltd. During the summers of 1956 and 1957 an extensive program of diamond drilling, geophysical surveying and geologic mapping was completed.

The glacial geology of the region is described fully by Neilson (16, 20). The direction of ice movement was south-southwesterly as shown by striae and drumlin directions. Ground moraine is abundant, consequently covering much bedrock geology. Drumlins are common, and glacio-fluvial deposits include eskers, outwash valley trains, sand plains and deltaic deposits. These deposits are not discussed in the following section on regional geology, which treats only bedrock geology.

REGIONAL GEOLOGY

Sam Gunner Group

The Sam Gunner group of sediments and volcanics is here named from the area of excellent exposures just south of Lake Sam Gunner (Fig. 2).

These rocks were formerly termed Early Precambrian "Keewatin-type" sediments and volcanics (15, 18). The rocks of sedimentary origin consist of metamorphosed pebble conglomerate, quartzite, graywacke and fine-grained arkose. The extrusive rocks are mainly dark, fine-grained andesite lavas. Neale (15) also reported some tuffs.

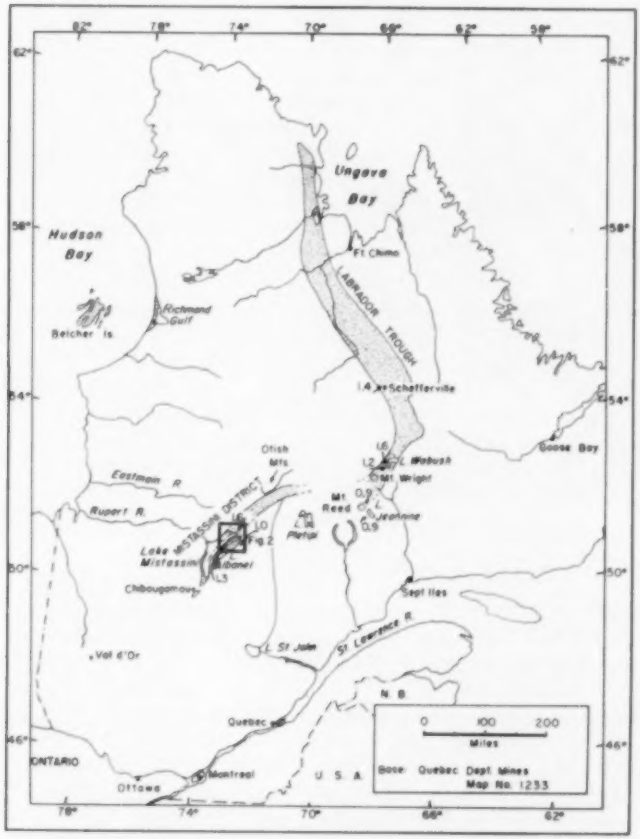


FIG. 1. Index map of Quebec showing the location of the Mistassini district and approximate locations of dated samples with K-A ages in billion years. Generalized areas of iron-bearing and associated sediments shown as stippled.

The rocks of this group lie within a narrow band about one mile wide, extending from the Takwa Mountains east-southeast to the Temiscamie River. Their attitude is essentially vertical with a nearly east-west strike.

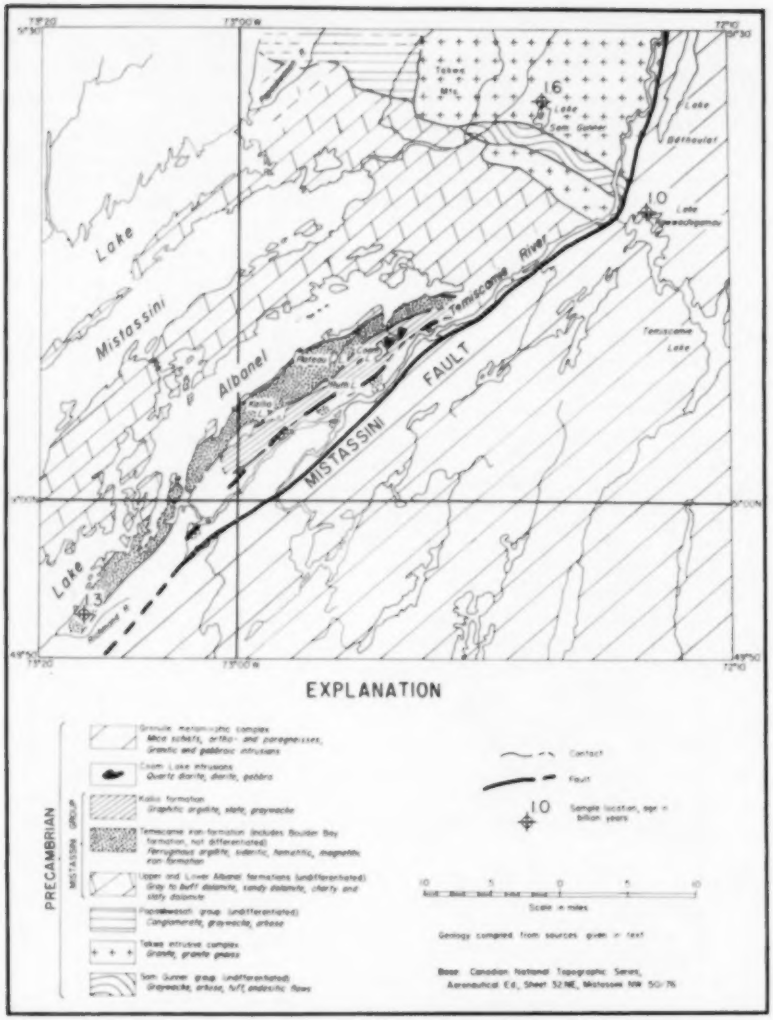


FIG. 2. Generalized geologic map of the Lake Albanel Iron Range, Quebec.

Takwa Intrusive Complex

The name Takwa intrusive complex is proposed here, because of the abundant outcrops in the Takwa Mountains, for rocks previously designated only as "Early Precambrian intrusives" by Neilson (18) and Neale (15).

The main mass of the complex lies in the area of the Takwa Mountains, east to the Temiscamie River, and for an undetermined distance to the north, although there is a thin band of hornblende granite south of the sediments of the Sam Gunner group.

Pink granite and porphyritic microcline granite are the most common rock types. A narrow band of diorite gneiss extends west of the western end of the Sam Gunner group, but this may be an altered phase of the older sedimentary sequence. Along the northern edge of the Sam Gunner group, a gray to pink biotite granite gneiss has been injected, at least in part, *lit-par-lit*. This gneiss is considerably contaminated and contains partly digested inclusions of biotite- and hornblende-rich rocks as well as recognizable inclusions of rocks of the Sam Gunner group. Thus, the Takwa intrusive complex is definitely younger than the Sam Gunner group. Further, Neilson (18) considers the hornblende granite south of the Sam Gunner group to be older than the pink granite to the north because the southern mass is cut by dikes of pink granite.

Papaskwasati Group

The Papaskwasati group consists of relatively unmetamorphosed pebble conglomerate, sandstone, quartzite and graywacke. This group lies to the west of the Takwa Mountains and was named by Neilson (18), for outcrops along the Papaskwasati River.

These rocks dip gently and lie unconformably on the Takwa complex. Neilson (18) considers the upper member of this group to be conformable with the overlying dolomite of the Mistassini group. He also correlates the Papaskwasati group with the Chibougamau series near Chibougamau to the south which was described by Mawdsley and Norman (14).

Mistassini Group

Barlow (1) appears to have been the first to apply the name "Mistassini" to the succession of dolomite, quartzite, iron-formation and slate in and around Lake Mistassini and Lake Albanel. However, he and subsequent writers have referred to these rocks as the "Mistassini Series." As noted by Neilson (20, footnote p. 15) the term group is preferable, because it is a rock term with no particular time significance (see also 2, p. 126).

The rocks of the group lie within the basin partially occupied by Lake Mistassini and Lake Albanel. Excellent exposures may be seen on the islands and shores of both lakes in low-lying cuestas and between the east shore of Lake Albanel and the Temiscamie River.

Lower and Upper Albanel Formations.—Wahl (25, p. 10) seems to have been the first to use the names Lower Albanel and Upper Albanel for the dolomites of the Mistassini group. Both formations are dolomite and differ only in detail.

The lower part of the Lower Albanel formation is characterized by argillaceous and slaty dolomite. Other members are defined by their color and bedding characters. The Upper Albanel formation is sandy dolomite and

dolomitic sandstone with fossil cryptozoa or algae and associated anthraxolite in its upper part. The total thickness of the Albanel dolomites is estimated by Neilson (16, p. 50–51) to be between 6,500 and 8,400 feet.

Boulder Bay Quartzite.—The name Boulder Bay has been suggested by J. M. Neilson (19) for the quartzite that is well exposed in the vicinity of Boulder Bay on Lake Albanel.

In outcrop the quartzite is vitreous white or light gray. It generally contains more than 90 percent of rounded quartz grains which show excellent overgrowths. The matrix may be chloritic with some siderite or dolomite, minor amounts of chert, small grains of plagioclase and zircon. In at least one locality the quartzite has boulders of dolomite at the base. In some places the Boulder Bay quartzite grades upward into the lower member of the Temiscamie iron-formation by an increase of carbonate and chlorite. The thickness ranges from 20 to 50 feet.

Temiscamie Iron-formation.—The iron-formation is about 700 feet thick and has been divided into six members on the basis of lithology (21).

The *lower argillite member* is a rock composed essentially of fine-grained muscovite and other layered silicates. It is dense black and thinly bedded. The thickness ranges from 9 to 40 feet.

The *lower sideritic chert member* composed of thick sideritic chert beds alternate with thin iron carbonate beds containing stilpnomelane. The thickness ranges from 20 to 100 feet.

The *magnetitic chert member* economically the most important member of the Temiscamie iron-formation. Magnetite and hematite occur with siderite and ankerite in a groundmass of quartz and chert. Over a strike length of 35 miles, parallel to the east shore of Lake Albanel, the thickness of the magnetitic chert member ranges from 73 to 195 feet.

The *upper argillite member* is similar in appearance to the lower argillite member. However, in contrast to it ankerite and siderite are the most abundant minerals and stilpnomelane is common. Various beds may be dark green or reddish brown as well as black. This member may be as thin as 5 or as thick as 45 feet.

A *magnetitic iron-silicate member* is not extensive, and is probably a lens within the upper argillite member. It occurs only in some of the fault blocks along the Temiscamie River. Magnetite is scattered or concentrated in thin layers. Plates of stilpnomelane make up most of the matrix of the magnetitic layers, with light-colored layers of chert, iron carbonate and minnesotaite occurring between the black magnetitic beds. The thickness of this member is difficult to determine because of much repetition by faulting; however, it is close to 100 feet.

An *upper sideritic chert member* is very similar to the lower sideritic chert member in mineralogy and bedding. The presence of oölites and granules and the absence of much minnesotaite in the upper member serve to distinguish it from the lower member. It has been computed to be at least 300 feet thick.

Kallio slate.—Wahl (25, p. 19) considered this sequence of rocks to be a member of the Temiscamie iron-formation. Neilson (16) elevated the unit

to the rank of formation and gave the name Kallio to it for the excellent exposures in the vicinity of Kallio Lake.

The Kallio formation consists of argillite, slate and graywacke. In thin section angular grains of quartz may make up as much as 80 percent of the rock. Plagioclase grains may also occur. Graphite, either with or without fine-grained pyrite, is ubiquitous, and along with mica, is a main constituent of the groundmass. In the slaty facies of the formation, graphite may make a thin section entirely opaque.

The Kallio formation is probably transitional with the underlying upper sideritic chert member of the Temiscamie iron-formation. No rocks have been found stratigraphically above the Kallio formation; thus it is believed to be the youngest consolidated sedimentary rock in the area.

Coom Lake Intrusions

In the vicinity of Coom Lake outcrops of quartz diorite, hornblende diorite, norite and gabbro, variously altered, have been described by Wahl (25, p. 19–20) and Neilson (16, 17). These outcrops may be parts of one intrusive mass. The Coom Lake intrusions are clearly younger than the Kallio formation, cutting across the bedding of the slates; however, their age relative to the rocks of the Grenville metamorphic complex is not known.

Grenville Metamorphic Complex

The southeastern part of the map area (Fig. 2) is underlain by igneous and metamorphic rocks of diverse types and probably of different ages. They are separated from the sediments of the Papaskwasati and Mistassini groups by the Mistassini fault (Huron-Mistassini or Grenville fault). These rocks are part of an extensive region, the Grenville subprovince of the Precambrian shield of eastern Canada. The "Grenville" has long been the subject of controversy, much of which revolves around the usage of words (24). In addition to its use as a physiographic-structural term (subprovince), the word "Grenville" has been variously employed: "Grenville rocks," "Grenville series," "Grenville orogenic belt," etc. The multiplicity of terms associated with the Grenville reflects the growth of geologic thinking concerned with Precambrian stratigraphy.

The rocks that lie southeast of the Mistassini fault zone are part of the so-called "Grenville problem." These rocks are not a lithic unit nor is it likely that they were formed within a limited time, but what they do appear to have in common is that they were more or less metamorphosed at approximately one billion years ago. For this reason they are referred to here as the Grenville metamorphic complex, in the sense that the metamorphism was impressed upon all of them at about the same time. The general strike of these rocks is northeast-southwest. The most common rock type is paragneiss (25, p. 7; 20, p. 8), and it is generally accepted that these gneisses are highly metamorphosed and granitized sediments. The gneisses extend both to the north and south of the area discussed and consist of garnetiferous-hornblende

gneiss, mica gneiss and injection gneiss. They are commonly fine to medium grained, dark colored and with good foliation or lineation.

Near the western margin of the large mass of gneiss, in the vicinity of the fault zone, foliated orthogneisses (25, p. 9) and non-foliated rocks have been emplaced. These rocks generally range in composition from syenite to granodiorite. Although the main mass of the acid intrusive rocks is at the western margin of the complex, rocks of similar lithology and field relationships occur 10 to 15 miles farther east. The contacts are typically sub-parallel to the foliation in both the granite orthogneiss and the mica paragneiss. The orthogneiss commonly exhibits foliation, but it is often difficult to discern.

In the area adjoining Lake Béthoulat near the northeast corner of the map area is a large mass of gabbro and feldspathic gabbro. Neale (15, p. 8) states that this mass truncates the structural trend of the paragneisses and in turn is cut by dikes of granitic composition. Neilson (17, p. 4) found similar rocks and relationships to the south along the Temiscamie River. He later described lithologically similar but smaller intrusions still farther south and states that this rock "appears to be intrusive into pink granite, and it is cut by several narrow, northwesterly striking dykes of pegmatitic granite" (20, p. 13). It seems most probable, therefore, that these gabbroic rocks are younger than the paragneisses but older than the granites and orthogneisses.

STRUCTURE

The map area (Fig. 2) is comprised of three major units of markedly contrasting structure: the Grenville metamorphic complex with a northeast-southwest trend, the Takwa intrusive complex and Sam Gunner group with an east–west trend, and the Papaskwasati and Mistassini groups dipping gently to the southeast. All three abut against or are terminated along the Mistassini fault zone, which is the major structural feature of the area.

The oldest rocks are the schistose series of volcanics, meta-sediments and associated intrusives of the Sam Gunner group. These rocks are essentially vertical in attitude and strike about east–west. They are intruded by the Takwa complex. The ortho- and paragneisses of this complex also dip at high angles and strike about east–west. The Sam Gunner group and the Takwa complex are cut off to the east near the Temiscamie River by the northeast–southwest trending Grenville metamorphic complex. The juxtaposition occurs along the well established Mistassini fault zone, here paralleling the east bank of the Temiscamie River. This fault zone extends to the southwest where it is known as the Huron-Mistassini fault. It has also been called the Grenville fault or the Grenville front.

South of the area of the Sam Gunner group and the Takwa complex and west of the fault zone lie the relatively unmetamorphosed sediments of the Papaskwasati and Mistassini groups. Within most of the area they dip gently to the southeast. However, near the Temiscamie River the upper members of the Upper Albanel dolomite as well as the three immediately overlying younger formations of the Mistassini group, including the Temiscamie iron-formation, are much deformed and occur as fault blocks that dip

steeply to the southeast and are in places overturned. This increase in deformation close to the Temiscamie River is attributed to movement along the Mistassini fault zone. Toward Lake Albanel, away from the Temiscamie River, the iron-formation exhibits a few minor rolls. A series of *en echelon* faults striking northeast and having a nearly vertical dip lie in the Kallio Lake-Ruth Lake-Plateau Lake area. The largest of these faults has a vertical displacement of about 500 feet and a strike length of over eight miles.

L. C. Coleman (personal communication, 1957) found that north of the map area the Mistassini fault bends more to the east and passes about two miles north of Lake Pletipi. From this point it probably proceeds eastward to the vicinity of Mt. Reed. North and east of the map area and north of the eastern extension of the Grenville fault, sedimentary rocks of the Indicator Lake Series (Otish Mountains group, (2), p. 129) similar to those of the Mistassini group have also been reported (22, p. 17). Iron-formation occurs northeast of Lake Pletipi, at Mt. Reed and at Mt. Wright.

COMPOSITION OF THE TEMISCAMIE IRON-FORMATION

The approximate bulk composition of the Temiscamie iron-formation, excluding the lower argillite member, is given by the chemical analysis (Table 1, No. 1) of a composite sample. This sample was made up from core of

TABLE 1

CHEMICAL ANALYSES OF IRON-FORMATIONS

	1	2	3	4
SiO_2	31.22	51.12	41.10	39.52
Al_2O_3	.14	1.31	1.88	.80
TiO_2	.02	tr.	.04	.15
P_2O_5	.13	.04	1.28	.02
Fe_2O_3	12.58	10.81	12.90	1.05
FeO	25.74	23.86	21.34	31.67
MgO	3.94	3.26	3.98	2.88
MnO	.68	.46	2.42	.99
CaO	5.17	.75	2.05	.59
Na_2O	.05	tr.	—	—
K_2O	.10	tr.	—	—
H_2O^+	.54	3.43	1.53	.92
H_2O^-	.06			
CO_2	19.69	4.77	11.60	21.15
C	n.d.	—	.17	
Total	100.06	99.81	100.29	99.80
Total Fe	28.81	26.11	25.63	25.34

1. Temiscamie iron-formation, composite sample of core from five diamond drill holes representing the Temiscamie iron-formation, except for the lower argillite member. Total thickness is approximately 535 feet. C. O. Ingamells, analyst, Rock Analysis Laboratory.

2. Main Mesabi district, Minnesota, average composition computed by Gruner (8, Table 11) from 14 chemical analyses of unaltered iron-formation.

3. Cuyuna district, Minnesota, average composition computed by Gruner (8, Table 11) from five chemical analyses.

4. Gogebic district, Wisconsin-Michigan, average composition computed by Gruner (8, Table 11) from four chemical analyses.

five diamond drill holes and represents a thickness of about 535 feet. Included in the table for comparison are averages computed from chemical analyses of the iron-formations from the main (central) Mesabi and Cuyuna districts of Minnesota, and the Gogebic district of Wisconsin and Michigan.

The chemical analyses show some striking similarities, but at the same time some equally important differences. Of particular interest is the tenor of total iron (Fe) which ranges from 25.3 to 28.8 percent and the relatively small contents of alumina and of titania. The average TiO_2 content of the iron-formation of the Gogebic district, if the figure of 0.15 percent is reliable, is many fold greater than that of the Mesabi, Cuyuna and Mistassini districts. Similarly, the P_2O_5 content of the Cuyuna district (1.3 percent) is notably high, ten times that of the Temiscamie iron-formation (0.13 percent) and much greater than the averages for the Mesabi (0.04 percent) and Gogebic (0.02 percent) districts.

The large percentage of CO_2 (19.7 percent) in the Temiscamie iron-formation composite reflects the large content of siderite and ankerite, and is notably similar to the calculated 21.2 percent of CO_2 for the Gogebic district. The CO_2 contents for the Cuyuna and Mesabi districts are appreciably lower, 11.6 and 4.8 percent, respectively. In its relatively large content of CaO (5.2 percent) the Temiscamie iron-formation is in sharp contrast to the other districts, the closest approach being 2.1 percent for the Cuyuna district. Unlike lime, magnesia appears to be relatively uniform, ranging from 2.9 to 4.0 percent. The alkalies are in small to negligible amounts.

In summary, the important chemical features of the Precambrian iron-formations of the four districts are the low contents of alumina and titania, the similarity in total iron content, and the variability of the other constituents in which relative deficiencies appear to be compensated largely in the silica contents. Thus, in a general way, CO_2 and SiO_2 vary inversely.

AGE AND CORRELATION

The similarity in chemical composition of the Temiscamie iron-formation with those of the Lake Superior region has been noted. Chemical analyses of the iron-formations of the Labrador trough are not available for comparison. Wahl (25) concluded that the similarity in stratigraphy and lithology of the Mistassini basin and of the Labrador trough indicates that the sediments were deposited at approximately the same time and probably in the same epicontinental sea. Bergeron (2) also favors the correlation. There are also similarities in the stratigraphic succession of the Mistassini and Lake Superior districts. The iron-formations are underlain by quartzite and overlain by argillite or "slate." Unlike the Pokegama quartzite of the Mesabi district of Minnesota which lies on an erosion surface cut on granite and metamorphic rocks, the Boulder Bay quartzite of the Mistassini district overlies a thick succession of Albanel dolomites and Papaskwasati clastic sediments. In this respect the stratigraphic succession resembles the iron districts of Wisconsin and Michigan (12, 13). The correlation of Precambrian rocks in widely separated regions on the basis of composition and stratigraphic

succession is not always dependable; environmental conditions may have been duplicated, and as a result similar rocks may have been deposited at different times.

In August of 1957 a series of samples was collected (S. S. G. and T. T. Q.), and three of these have been utilized for A^{40}/K^{40} age determinations. The locations of the samples are shown on Figure 2, and the results are given in Table 2.

Sample 1 is fresh clean biotite from a dark-gray compositionally banded gneiss collected on the northwestern shore of Lake Kawwachigamau. The greater part of the rock is light-gray, fine-grained quartz and feldspar. The banding results from black schlieren or layers of biotite, 1–2 inches long and approximately $\frac{1}{8}$ inch wide, that make up about 10 percent of the gneiss. Numerous large grains of quartz and some of feldspar are conspicuous. A thin section shows that the rock has undergone recrystallization, and the

TABLE 2

RADIOACTIVITY DATES FOR SAMPLES FROM MISTASSINI DISTRICT

Sample No.	K$_2$O pct	K^{40} ppm*	A^{40} ppm	A^{40}/K^{40}	K-A Age b y	Rb-Sr Age b y
1	9.03	9.05	0.702	0.0776	1.00	
2	7.33	7.34	1.10	0.150	1.61	1.67
			1.09	0.149	1.60	
3	8.75	8.77	0.957	0.109	1.29	
			0.952	0.109	1.29	

* Parts per million by weight based on isotopic abundance of 1.21×10^{-4} g/g K. K-A constants: $\lambda_e = 0.585 \times 10^{-10}$/yr.; $\lambda_\beta = 4.72 \times 10^{-10}$/yr. Rb-Sr constants: $\lambda_\beta = 1.39 \times 10^{-11}$/yr.

1. Paragneiss, Grenville metamorphic complex, Lake Kawwachigamau, 51°18′N, 72°18′W, Cat. No. KA-197.
2. Granite gneiss, Takwa complex, Lake Sam Gunner, 51°25′N, 72°29′W, Cat. No. KA-198.
3. Lower argillite, Temiscamie iron-formation, Lake Albanel, DDH R14, 253 feet, 50°52′N, 73°15′W, Cat. No. KA-211.

texture is granoblastic and poikiloblastic. The plagioclase, andesine, contains numerous inclusions of small quartz grains, variously oriented flakes of biotite, and a few fractured grains of sphene. It is extensively replaced by microcline with the development of antiperthite. Sericite and calcite are minor alteration products. Quartz, in addition to the abundant small inclusions in the porphyroblastic plagioclase, occurs in larger mutually sutured grains. The estimated mineral composition of the thin section is quartz, 30; plagioclase, 30; microcline, 30; biotite and other minerals, 10 percent. The composition is that of a quartz monzonite, but the gneiss probably is of sedimentary origin.

Sample 2 is biotite separated from fine-grained, gray to pink gneiss of the Takwa complex from outcrops just northwest of Lake Sam Gunner. This locality is 11 miles northwest of Lake Kawwachigamau and approximately 8 miles west of the Mistassini fault. A thin section shows a granoblastic,

cataclastic texture characterized by mortar structure. The foliation of the rock results from the alignment of biotite flakes which are not segregated in bands as in the paragneiss of Sample 1. Andesine (An_{35}) makes up 50 percent of the thin section, and the grains, averaging about 2 mm across, are two to three times larger than the quartz and K-feldspar. Much of the andesine is untwinned and is altered to sericite and epidote. The K-feldspar is unaltered and includes both orthoclase-perthite with coarse vein- and braid-type plagioclase and microcline-microperthite with minor films of plagioclase. The estimated mineral composition of quartz, 30; andesine, 50; K-feldspar, 15; biotite and others, 5 percent, corresponds to that of granodiorite. Whether the gneiss is of igneous or of sedimentary origin is uncertain; it may represent a metamorphosed graywacke of the Sam Gunner group.

Sample 3 of the lower argillite member of the Temiscamie iron-formation is from a diamond drill hole in the southwestern corner of the map area (Fig. 2). The core is fresh, dark-gray argillite. Because of the fine grain size no mineral separation was attempted. The rock was crushed and sieved, and the 40–60 mesh fraction was used in the age determination. X-ray and petrographic examinations showed principally sericite with some quartz, chlorite and K-feldspar. The feldspar is estimated at 15 percent and appears to be detrital, so that the argillite sample is somewhat uncertain for dating purposes; however, a careful search of the cores from a number of holes failed to reveal more useful material. The age of 1.3 b y obtained for the argillite may approximate the time of lithification, but no great significance is attached to the number because of the uncertainty of origin and composition.

The 1.0 b y age for the paragneiss from Lake Kawwachigamau agrees well with radioactivity dates for many samples from the Grenville subprovince by U-Pb techniques (3, 5, 23). The Grenville may represent sediments deposited at different times and intruded by magmatic rocks of different ages, but the metamorphism is well established at approximately one billion years ago.

The biotite (Sample 2) from the gneiss of the Takwa complex was dated by both the K-A and the Rb-Sr techniques. The analytical data for the K-A determination are given in Table 2. The Rb-Sr analysis gave 204 ppm of Rb^{87} and 4.77 ppm of radiogenic Sr^{87}, the latter being 71 percent of the total Sr^{87} found. The K-A and Rb-Sr ages of 1.60 b y and 1.67 b y, respectively, agree within the error of the methods. If on the basis of the agreement of the two age determinations 1.6 b y is accepted as the time of orogeny that developed the east–west structural trend in the Takwa area, the time of deposition of the overlying sediments of the Papakwasati and Mistassini groups is limited between 1.6 and 1.0 billion years. The Temiscamie iron-formation, then, cannot be correlated with the iron-formations of the Lake Superior region, because the latter were involved in an orogeny dated at approximately 1.7 b y (7).

A late Precambrian age of the Mistassini rocks is implied by Cumming, Wilson, Farquhar and Russell (3) in their suggestion that these rocks are part of a "secondary Grenville or Huronian Province" derived from the

Grenville mountains. They also proposed primary and secondary provinces in Labrador and Ungava intermediate in age between the Grenville (0.9–1.1 b y) and the Keewatin (2.3–2.5 b y). The granitic and high-grade metamorphic rocks east of the Labrador trough are the primary province; the less metamorphosed rocks of the trough are the secondary province. On the basis of ages computed from the ratios of Pb isotopes in analysed galenas they suggest that both of these provinces were active 1,500 million years ago. Harrison (10) states that ages from Pb isotopes of samples of galena from five different veins cutting the Ungava rocks range from 1,630 to 2,320 million years. The locations and analytical data are not given.

A sample of the Menihek slate from Knob Lake, obtained through the courtesy of the Iron Ore Company of Canada, was dated at 1.4 b y by the K-A method at Minnesota (Table 3). The sample is hard, dark-gray to black, laminated rock with poorly developed slaty cleavage. The Menihek slate (9) is the youngest formation of the Knob Lake group and overlies the Soko-

TABLE 3

K-A Ages for Samples from the Labrador Trough and Mt. Wright Area

Sample No.	K_2O pct	K^{40} ppm	A^{40} ppm	A^{40}/K^{40}	Age b y
4	4.80	4.81	0.600	0.125	1.42
5	10.02	10.04	0.685	0.0682	.90
6	10.83	10.85	0.748	0.069	.91
7	10.56	10.58	0.710	0.067	.89

Constants given in Table 2.

4. Menihek slate from Knob Lake. Cat. No. KA-322
5. Biotite from coarse-grained schist in dolomitic marble, below iron-formation, Mt. Reed, Quebec Cartier Mining Company, Cat. No. KA-148.
6. Muscovite from KA-148; same as No. 5 above.
7. Muscovite from coarse-grained schist cored in diamond-drill hole at Jeannine Lake, Quebec Cartier Mining Company, Cat. No. KA-149.

man iron-formation. A thin section shows well-crystallized and aligned sericite, and X-ray analyses indicate muscovite, quartz, chlorite, and a very small amount of K-feldspar. The 1.4 b y date for the Menihek slate is considered a minimum age. The complexity of the geologic history of the region is indicated in the K-A ages obtained for rocks from the Wabush Lake and Mt. Wright areas (Fig. 1).

Two samples of the basement gneisses west of Wabush Lake have been dated by the geochronology group of the Massachusetts Institute of Technology. The K-A ages (11) for these samples are 1.58 b y and 1.25 b y. A third sample of the Katsao formation from the same area gave a K-A age of 1.12 b y. Biotite and muscovite separated from coarse-grained schist from Mt. Reed and from Jeannine Lake, obtained through the courtesy of the Quebec Cartier Mining Company, have been dated at Minnesota (Table 3). The age of 0.9 b y indicates that these rocks have been involved in the Grenville orogeny, and the increasing K-A ages to the north suggest that the K-A ages are dependent on the proximity of the dated samples to the belt of Gren-

ville orogeny. This line of reasoning suggests that in the Mistassini district to the southwest the dated rock also may have been affected by the Grenville orogeny.

Biotite is highly susceptible to recrystallization with loss of radiogenic argon, so that K-A ages commonly are survival values, dating the last thermal history (7). Recent investigations (4) in the Appalachian Mountains are instructive in this regard. The Baltimore gneiss of Maryland and Pennsylvania, on the basis of concordant U-Pb dates for zircon and a Rb-Sr date for microcline, is 1,000 to 1,150 million years old; however it was metamorphosed during the Appalachian orogeny (300–350 m y) with the result that the microcline lost argon and the biotite lost both argon and strontium. Rb-Sr ages for four samples of biotite range from 305 to 390 m y. The corresponding K-A dates on three samples are in each case greater than the Rb-Sr values and range from 338 to 550 m y. The loss of argon and of strontium by recrystallization of the biotite in the Baltimore gneiss in terms of time is of the order of 500–850 million years. If it is assumed that the biotite of the Takwa gneiss has undergone a similar loss of argon and of strontium as a result of the Grenville or of an earlier orogeny, the true age of the gneiss might well be in excess of 2 billion years and in the range of the Keewatin continental nucleus as proposed by Cumming, Wilson, Farquhar and Russell (3).

The relatively unmetamorphosed sedimentary rocks of the Papaskwasati and Mistassini groups that overlie the Takwa complex northwest of the Mistassini fault, in comparison with the high-grade metamorphic gneisses of the Grenville complex southeast of the fault, suggest that metamorphism of the latter was not accomplished in the present site. Only subsequent to the Grenville orogeny were the gneisses brought into juxtaposition with the rocks of the Mistassini group and the Takwa gneiss. The possibility of a pre-Grenville orogeny therefore should be considered.

Assuming for purposes of this discussion that Wahl's (25) correlation is correct and that the rocks of the Mistassini district and of the Labrador trough region were deposited in the same epicontinental sea, the geologic history can be interpreted on the basis of three major periods of orogeny. In the Mistassini district the oldest orogeny resulted in the folding and metamorphism of the Sam Gunner group and was accompanied by emplacement of the Takwa intrusive complex. The Papaskwasati and Mistassini groups were deposited on a surface cut on the rocks of the Sam Gunner group and of the Takwa complex. The source of the sediments probably was the more or less reduced mountains to the west, but a second speculative source may have been an island arc to the east. The accumulation of a thick sequence in the eastern eugeosynclinal portion of the trough was followed by folding accompanied by metamorphism, granitization and granite intrusion. The rocks in the vicinity of Lake Mistassini resting on the craton were not involved in the tight folding and high-grade metamorphism. The time of folding based on dates from the Labrador trough was at least 1.5 billion years ago. The 1.6 b y date obtained for the Takwa gneiss may reflect this orogeny. The mountain belt formed during this second orogeny provided the sediments which

in turn were built into mountains during the Grenville orogeny. The Grenville mountains may have been roughly parallel to the structural trend developed in the Mistassini district during the preceding (1.5+ b y) orogeny but cut across the structure of the Labrador trough. In this interpretation rocks that were involved in at least two previous orogenies were included in the Grenville mountain building, although to what extent is unknown. It appears certain that the rocks of the southern end of the Labrador trough were involved and cannibalized during the Grenville orogeny, and by analogy the rocks of the Mistassini district may have had a similar history. At the same time the writers feel that the possibility of the Mistassini rocks being younger than 1.6 b y has not been eliminated. The problem appears to be amenable to solution with additional field studies supplemented by radioactivity dating of a greater number of samples than could be undertaken for the present investigation.

ACKNOWLEDGMENTS

Field work was done by Quirke while in the employ of Albanel Minerals Ltd. during the summers of 1956 and 1957. The company also generously supported much of the research during the academic years of 1957–58 in the preparation of a Ph.D. thesis (21) from which some of the data presented in this paper have been taken.

We are indebted to the Cleveland-Cliffs Iron Company, Ishpeming, Michigan, to M. J. O'Brien Ltd., Ottawa, Ontario, and to Albanel Minerals Ltd., Port Arthur, Ontario, for permission to publish. It is a pleasure to acknowledge the cooperation and valuable assistance received from M.W. Bartley, B. H. Boyum, J. C. Craddock, J. W. Gruner, J. M. Neilson and W. R. Sutton.

The A^{40}/K^{40} age determinations were made possible through the geochronology program at the University of Minnesota supported by a grant from the National Science Foundation. The cost of these analyses as well as of the chemical analysis of the Temiscamie iron-formation was financed by a grant from the Graduate School of the University of Minnesota to Goldich, and the cost of manuscript preparation was defrayed by a Faculty Research Award of the University of North Dakota to Quirke.

UNIVERSITY OF NORTH DAKOTA,
GRAND FORKS, NORTH DAKOTA
UNIVERSITY OF MINNESOTA,
MINNEAPOLIS 14, MINNESOTA
UNIVERSITY OF MINNESOTA,
MINNEAPOLIS 14, MINNESOTA
May 21, 1959

REFERENCES

1. Barlow, A. E., Faribault, E. R., and Gwillim, J. C., 1911, Geology and mineral resources of the Chibougamau region, Quebec: Quebec Dept. Mines and Fisheries, Mines Branch, p. 131–133.
2. Bergeron, Robert, 1957, Late Precambrian rocks of the north shore of the St. Lawrence River and of the Mistassini and Otish Mountains areas, Quebec, *in* the Proterozoic in Canada: Royal Soc. Canada, Spec. Pub. 2, p. 124–131.

3. Cumming, G. L., Wilson, J. T., Farquhar, R. M., and Russell, R. D., 1955, Some dates and subdivisions of the Canadian Shield: Geol. Assoc. Canada Proc., v. 7, p. 27–80.
4. Davis, G. L., Tilton, G. R., Aldrich, L. T., and Wetherill, G. W., 1958, The age of rocks and minerals, *in* Ann. Rept. of the Director, Geophysical Laboratory, Carnegie Inst. Wash., 1957–58, p. 176–181.
5. Farquhar, R. M., and Russell, R. D., 1957, Dating the Proterozoic of Canada, *in* the Proterozoic in Canada: Royal Soc. Canada, Spec. Publ. 2, p. 28–32.
6. Gill, J. E., and others, 1957, The Proterozoic in Canada: Royal Soc. Canada, Spec. Publ. 2, 191 p.
7. Goldich, S. S., Baadsgaard, H., and Nier, A. O., 1957, Investigations in A^{40}/K^{40} dating: Am. Geophys. Union Trans., v. 38, p. 550.
8. Gruner, J. W., 1946, The mineralogy and geology of the taconites and iron ores of the Mesabi range, Minnesota: Iron Range Resources and Rehabilitation Commission, St. Paul, Minn., 127 p.
9. Harrison, J. M., 1952, The Quebec-Laborador iron belt, Quebec and Newfoundland: Geol. Survey Canada, Paper 52–20, p. 13.
10. ——, 1957, Proterozoic in Canada, *in* The Proterozoic in Canada: Royal Soc. Canada, Spec. Publ. 2, p. 3–9.
11. Hurley, P. M., and others, 1958, Investigation in Laborador: NYO-3937, Sixth Annual Progress Report for 1958, Massachusetts Institute of Technology, p. 129.
12. James, H. L., 1958, Stratigraphy of pre-Keweenawan rocks in parts of northern Michigan: U. S. Geol. Survey Prof. Paper 314-C.
13. Leith, C. K., Lund, R. J., and Leith, A., 1935, Pre-Cambrian rocks of the Lake Superior region: U. S. Geol. Survey, Prof. Paper 184, p. 10.
14. Mawdsley, J. B., and Norman, C. W. H., 1935, Chibougamau Lake map area, Quebec: Geol. Survey Canada Mem. 185.
15. Neale, E. R. W., 1952, Preliminary report on Béthoulat Lake area, Mistassini Territory, Quebec: Quebec Dept. Mines, Prelim. Rept. No. 264, 13 p.
16. Neilson, J. M., 1950, Geology of the Mistassini region, northern Quebec: Ph.D. thesis (unpublished), Univ. Minn., 156 p.
17. ——, 1950, Preliminary report on Temiscamie Mountains map area, Mistassini Territory, Quebec: Quebec Dept. Mines, Prelim. Rept. No. 238, 8 p.
18. ——, 1951, Preliminary report on Takwa River area, Mistassini Territory, Quebec: Quebec Dept. Mines, Prelim. Rept. No. 254, 9 p.
19. ——, 1952, Unpublished company report.
20. ——, 1953, Albanel area, Mistassini Territory, Quebec: Quebec Dept. Mines, Geol. Rept. No. 53, 35 p.
21. Quirke, Jr., T. T., 1958, Mineralogy and stratigraphy of the Temiscamie iron-formation, Lake Albanel iron range, Mistassini Territory, Quebec: Ph.D. thesis (unpublished), Univ. Minn., 115 p.
22. Robinson, W. G., 1956, The Grenville of New Quebec, *in* The Grenville Problem: Royal Soc. Canada, Spec. Publ. 1, p. 14–19.
23. Shillibeer, H. A., and Cumming, G. L., 1956, The bearing of age determination on the relation between the Keewatin and Grenville provinces, *in* The Grenville Problem: Royal Soc. Canada, Spec. Publ. 1, p. 54–73.
24. Thomson, J. E., and others, 1956, The Grenville Problem: Royal Soc. Canada, Spec. Publ. 1, 119 p.
25. Wahl, W. G., 1953, Temiscamie River area, Mistassini Territory, Quebec: Quebec Dept. Mines, Geol. Rept. No. 54, 32 p.

Economic Geology
Vol. 55, 1960, pp. 327–337

THE GENESIS OF CHRYSOTILE ASBESTOS IN THE CASSIAR ASBESTOS DEPOSIT, NORTHERN BRITISH COLUMBIA[1]

HUBERT GABRIELSE

ABSTRACT

A comparison of the Cassiar Asbestos serpentinite body with other ultramafic bodies in the McDame map-area of northern British Columbia suggests that the critical conditions leading to ore deposition at Cassiar were as follows:

1. Pervasive serpentinization of an ultramafic body resulting in mesh-structure serpentine, serpophite and bastite.
2. Development of abundant fractures in the serpentinite body.
3. Recrystallization of the serpentinite during low-grade metamorphism, perhaps equivalent to the upper part of the green-schist facies.

Rocks of the area were probably folded while the nearby Cassiar granitic rocks were emplaced. This deformation produced a complex system of fractures in the serpentinite body. In a low-grade, contact-metamorphic environment asbestos-forming material diffused into fractures of low rock pressure and crystallized to form chrysotile-asbestos veins.

INTRODUCTION

THE Cassiar Asbestos deposit is on the northwest flank of Mt. McDame in the Cassiar Mountains of northern British Columbia, approximately 100 miles by road from Watson Lake, Yukon Territory (Fig. 1). The property is owned and operated by Cassiar Asbestos Corporation, Limited, a subsidiary of Conwest Exploration Company, Limited. An account of the history and development of the mine was given recently by Smitheringale (6).

The Cassiar serpentinite body is one of many ultramafic bodies in the McDame map-area. It is the only one, however, in which asbestos of commercial importance has been found.

A detailed study of ultramafic bodies in the area indicates that the Cassiar serpentinite body has undergone an unusual combination of serpentinization, fracturing, and metamorphism. In this report an attempt is made to show how the geological history of this body differs from that of other bodies in the area.

GENERAL GEOLOGY

The McDame ultramafic rocks occur in a major southeasterly plunging synclinorium (Fig. 2). Two contrasting types of lithology are represented. Typical miogeosynclinal rocks comprise quartzite, limestone, dolomite, slate and argillite of Precambrian to Middle Devonian ages. Typical eugeosyn-

[1] Published with permission of the Director, Geological Survey of Canada.

clinal rocks comprise chert, argillite, argillaceous quartzite, greenstone and graywacke of Upper Devonian and Lower Mississippian ages and overlie Middle Devonian strata with apparent conformity. Ultramafic bodies have intruded the eugeosynclinal assemblage and are in turn cut by granitic rocks of the Cassiar intrusions.

FIG. 1. Index map.

Three thousand feet west of the asbestos deposit a stock of coarse-grained, porphyritic granite, separated from the Cassiar batholith by a 500-foot screen of contact-metamorphic rocks, has intruded Precambrian and Cambrian strata. Rocks on the Cassiar Asbestos property lie just within the outer limits of the contact-metamorphic aureole related to the granitic rocks. Greenstones near the mine commonly have a crystalloblastic texture and consist largely of tremolite-actinolite, zoisite, clinozoisite, sodic plagioclase and minor hornblende. These greenstones contrast with those farther east that typically have a diabasic or subophitic texture and are characterized by sodic plagioclase, augite, and alteration products of augite. Before alteration most of the volcanic rocks in the area were pyroxene andesites or basalts.

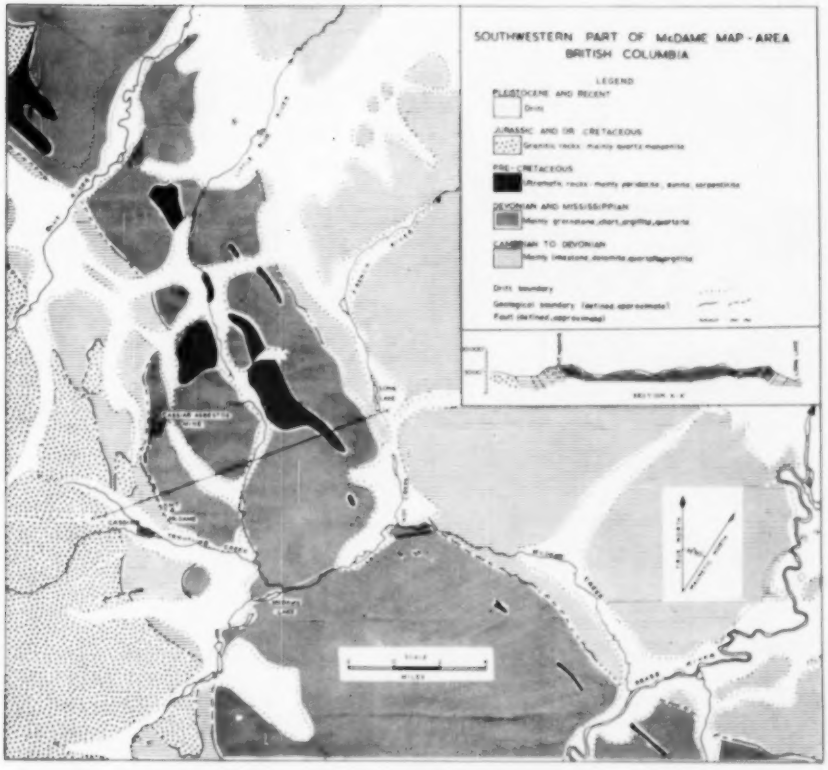


FIG. 2.

THE SERPENTINITE BODY AT CASSIAR

Chrysotile-asbestos veins at Cassiar occur in a mainly concordant, steeply dipping, lenticular serpentinite body that has intruded argillite, chert, quartzite and greenstone (Fig. 3). The ultramafic body has a maximum width of about 500 feet and a minimum length of 1,700 feet. The host rock consists of blocky, locally slickensided, light to dark green serpentinite containing scattered, glistening crystals of serpentine pseudomorphous after rhombic pyroxene. Magnetite is fairly abundant and occurs in microscopic veinlets or in veins as much as ¼ inch wide. The original rock was presumably a harzburgite.

Contacts between the ultramafic body and enclosing rocks are locally well exposed. Argillaceous rocks of the foot-wall are highly sheared, folded, and brecciated. Greenstones along the hanging-wall have been altered to cream-

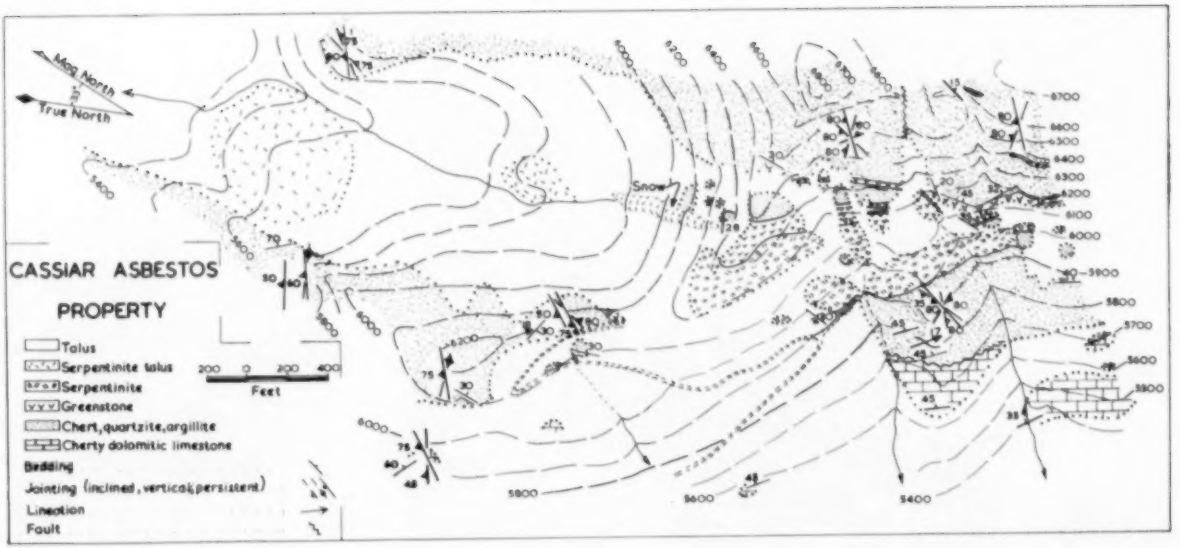

Mag North
True North
CASSIAR ASBESTOS
PROPERTY
Talus
Serpentinite talus
Serpentinite
Greenstone
Chert, quartzite, argillite
Cherty dolomitic limestone
Bedding
Jointing (inclined, vertical; persistent)
Lineation
Fault
200 0 200 400
Feet
Snow
6700
6600
6500
6400
6300
6200
6100
6000
5900
5800
5700
5600
5500
5800
5600
5400

FIG. 3.

colored, zoisite-quartz-tremolite hornfels. Adjacent to the hornfels and gradational into it over an unknown width is a zone of serpentinite that has been partly altered to fine-grained, dark green, chlorite-antigorite rock. This alteration zone forms an envelope around much of the central ore-bearing part of the body and contains little asbestos fiber. In places along the highly sheared footwall, however, high-grade asbestos occurs adjacent to the country rocks.

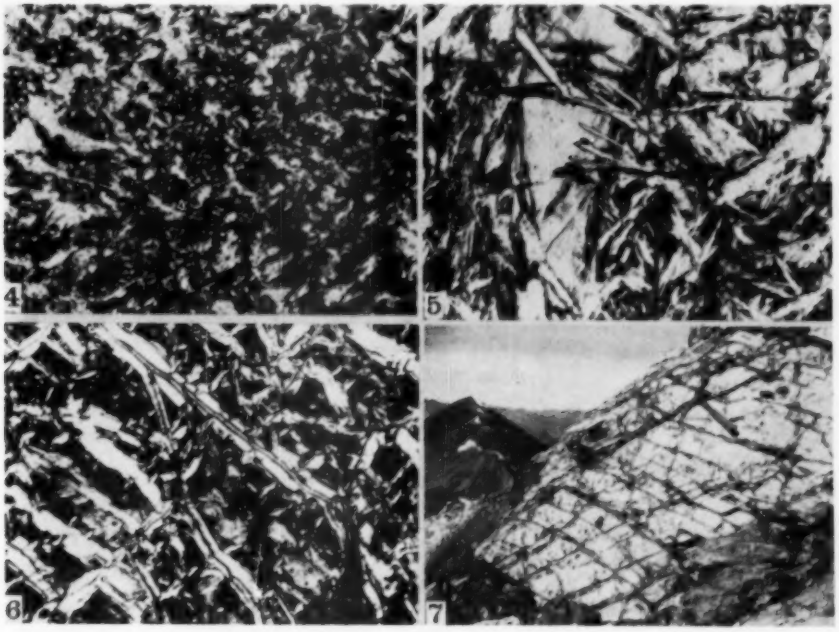


FIG. 4. Patchy serpentinite (mainly antigorite) from Cassiar Asbestos serpentinite body. × 55.

FIG. 5. Feathery, reticulated serpentine (antigorite). The feathery serpentine has almost completely replaced the mesh-structure serpentine and has partly replaced the bastite. × 100.

FIG. 6. Mesh structure serpentine (chrysotile) and serpophite (almost isotropic material). × 100.

FIG. 7. Joint pattern accentuated by asbestos veins on the Cassiar Asbestos property.

Mineralogy of the Cassiar Serpentinite Body.—Serpentines in the Cassiar serpentinite body and in other ultramafic bodies in the area were studied with the aid of the petrographic microscope, chemical analysis, differential thermal analysis, x-ray diffraction and electron microscope (3). Serpentines

in the ore-bearing part of the Cassiar serpentinite body are mainly textural varieties of chrysotile and antigorite and are classified as follows.

1. Patchy antigorite; appears to be the most abundant serpentine in the host rock; invariably is serpentine that borders asbestos veins; may include minor chrysotile (Fig. 4).

2. Antigorite pseudomorphous after rhombic pyroxene-bastite (Fig. 5).

3. Antigorite, feathery reticulated; a metamorphic serpentine replacing mesh-structure serpentine and bastite; relatively minor (Fig. 5).

4. Chrysotile; occurs as asbestos in veins; may also form part of the host rock.

5. Chrysotile, fine-grained, banded, homogeneous and waxy in hand specimen; very minor at Cassiar; occurs in veins as much as $\frac{1}{2}$ inch wide.

Mineralogy of Other Serpentinite Bodies in the McDame Area.—Most other serpentinites in the area consist of mesh-structure chrysotile (derived from olivine), serpophite (a poorly crystallized serpentine that is perhaps in part a silica-magnesium-water gel, also derived from olivine), and bastite (derived from orthopyroxene) (Fig. 6). Near the Cassiar batholith northwest of Blue River feathery, reticulated antigorite has resulted locally from the metamorphism of mesh-structure chrysotile, serpophite and bastite.

Fine-grained, banded, waxy chrysotile, although present in only very minor amounts at Cassiar, borders many asbestos veinlets in partly serpentinized dunites and peridotites elsewhere in the region.

TABLE 1

CHEMICAL ANALYSES OF TYPICAL MCDAME SERPENTINITES

	1	2	3	4	5
SiO_2	39.72	39.73	40.78	42.24	39.41
TiO_2	0.01	0.00	0.01	0.00	0.39
Al_2O_3	1.49	1.35	1.20	0.48	4.68
Fe_2O_3	5.30	4.26	3.37	1.37	2.38
FeO	2.87	0.98	0.04	0.16	3.98
MnO	0.10	0.08	0.03	0.05	0.27
MgO	36.91	39.54	40.47	41.88	35.52
CaO	0.14	0.00	0.00	0.00	0.14
Na_2O	0.00	0.00	0.00	0.00	0.00
K_2O	0.00	0.00	0.00	0.00	0.00
H_2O	11.76	12.41	12.76	12.49	12.03
H_2O	0.74	0.95	1.18	0.90	1.07
P_2O_5	0.00	0.00	0.00	0.00	0.13
Cr_2O_3	0.29	0.36	0.16	0.16	0.01
NiO	0.26	0.27	0.13	0.17	0.07
CO_2	0.07	0.18	0.21	0.06	0.06
Total	99.66	100.11	100.34	99.96	100.14

Analyst, John A. Maxwell, Geological Survey of Canada.

1. Serpentinite containing mesh-structure serpentine, serpophite, and bastite, west of French Lake.

2. Patchy serpentinite, Cassiar Asbestos property.

3. Fine-grained, waxy, banded chrysotile with minor patchy serpentinite, Cassiar Asbestos property.

4. Chrysotile asbestos, Cassiar Asbestos property.

5. Fine-grained antigorite and chlorite, upper contact of Cassiar Asbestos serpentinite body.

Chemical Analyses.—Chemical analyses of typical serpentinites in the area are given in Table 1. The greater amount of Al_2O_3 in the host rock than in the asbestos at Cassiar is consistent with analyses given by Kalousek and Muttart (4) for a number of asbestos deposits.

Asbestos Veins.—In a general way the chrysotile-asbestos veins at Cassiar are similar to those in many of the asbestos deposits in the Eastern Townships of Quebec (2, 5). The Cassiar serpentinite body has been highly fractured and most, if not all, fractures in the ore-zone contain asbestos.

FIG. 8. Joint pattern accentuated by asbestos veins on the Cassiar Asbestos property. Width of exposure about 20 feet. Photo by British Columbia Department of Mines.

Locally, the veins have a systematic arrangement (Figs. 7, 8). Some of the veins are parallel to joints enclosing strata and elsewhere in the synclinorium. These appear to be 'a-c' or cross-joints and related shear joints resulting from a northeast-southwest compression and attendant elongation parallel to the axis of the synclinorium. Flat-lying and gently dipping fractures, many of which contain long-fiber asbestos, are apparently tensional joints related to relative movements during folding of strata enclosing the serpentinite body. In addition to the major joints, many joints appear to have resulted from relative movements of blocks bounded by joints. The result of the deformation was a complex set of fractures that formed loci for the deposition of chrysotile asbestos.

Most of the asbestos occurs in cross-fiber veins in which the chrysotile crystals are oriented at large angles to the walls. One or more partings are generally present in the veins and are emphasized by magnetite grains or stringers and serpentinite chips. The partings are generally irregular, the irregularities being most pronounced in the widest veins. On the other hand, the vein-walls are, in many cases, remarkably planar regardless of the width of vein. This characteristic implies that the partings probably do not represent initial fractures that formed the loci of replacement veins. Matching irregularities in vein-walls are sufficiently abundant to indicate that fracture-filling played a dominant role in ore deposition.

Individual veins may persist for as much as 10 or 15 feet but generally they are much shorter, particularly where the fractures are densely spaced. They split, branch, and terminate either by merging with veins running in other directions or by pinching out. Short veins without apparent connection to other veins are commonly lenticular.

The fiber is exceptional both for length and quality. Fibers ranging from ½ to 1 inch in length are common. The milled product has relatively low iron content although magnetite is fairly abundant in partings and along the walls of veins. As will be pointed out below the low iron content of the asbestos may be due to the early accumulation of magnetite in fractures. Where cross-cutting relationships are present asbestos veins invariably cut magnetite veinlets.

Some veins show remarkable effects of post-vein shearing. Such deformation is most apparent near the foot-wall of the deposit. Off-setting of one vein by another, although not particularly common, points to deformation accompanying asbestos-formation.

Asbestiform Veins in Rocks Near the Asbestos Deposit.—In country rocks near the asbestos deposit many steeply dipping veins and veinlets containing quartz, tremolite, zoisite, and carbonate have a cross-fiber structure identical to that of the asbestos veins (Fig. 9). Many of these veins display a banding parallel to the walls similar to the wavy banding observed in the fine-grained banded chrysotile of the asbestos deposit.

Genesis of the Chrysotile Asbestos.—Before emplacement of the Cassiar granitic rocks the ultramafic body at Cassiar probably consisted essentially of mesh-structure chrysotile, serpophite, and minor bastite. This mineral assemblage is typical of all small ultramafic bodies in the area remote from the contact-metamorphic effects of the granitic rocks. Restriction of asbestos veins to the serpentinite and the general similarity in composition of the veins and host rock suggests that the vein material was derived from the host serpentinite and that the material had limited mobility. The following succession of events is postulated:

1. Folding and metamorphism of the serpentinite and enclosing rocks accompanied the emplacement of the Cassiar batholith. As a result the serpentinite body was complexly fractured and brought into a metamorphic environment perhaps equivalent to the upper part of the green-schist facies.

2. Recrystallization of the serpentinite and the diffusion of asbestos-forming material from the host rock into areas of low rock pressure promoted the growth of chrysotile asbestos. The slightly increased concentration of aluminum in the host serpentinite may have been an important factor in the formation of patchy antigorite (1). Recrystallization of serpophite probably resulted in a slight decrease in volume thus effectively increasing the volume of the low-pressure zones.

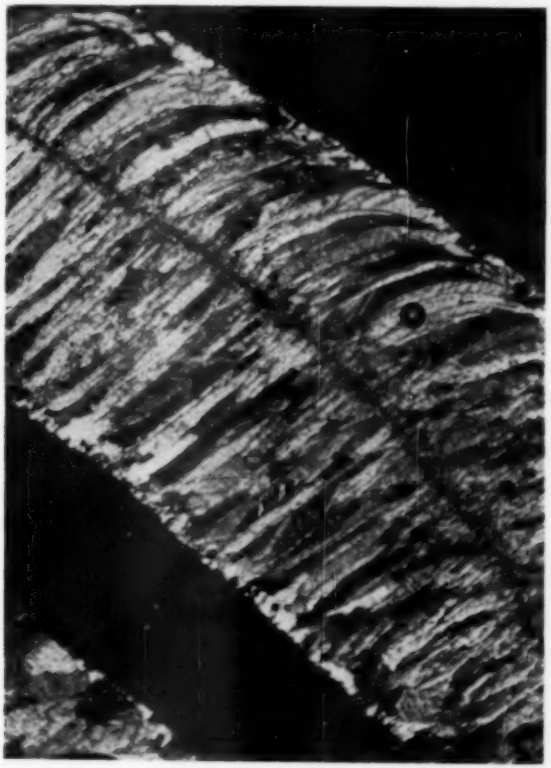


FIG. 9. Asbestiform calcite forming a "two-fiber" vein in calcareous argillite. Fine-grained material along the borders of the vein is quartz. × 20.

3. The growth of fiber in the single-fiber veins kept pace with the rate at which the walls moved apart. In the two-fiber veins the walls moved apart more rapidly than material could diffuse into the openings. Hence fiber grew from both walls in the direction of least pressure and finally met to form a central parting, the irregularity of which reflects the different rates of addition of material from place to place along the veins. Some of the

pre-asbestos magnetite, and serpentinite chips from the walls of the fractures were pushed outward on top of the growing fiber and thus accumulated along the partings. In many places the remainder of the magnetite formed the base on which the fiber grew. This hypothesis would explain why the magnetite is loosely bound to the asbestos.

4. Simultaneous with asbestos-formation and under similar conditions the quartz-tremolite-zoisite-carbonate veins were formed in the country rock. The composition of fibrous materials in these veins simply reflects the composition of the rocks in which they occur.

5. Metamorphism along the margins of the asbestos deposit produced the partial envelope of chlorite-antigorite rock. In places along the foot-wall later shearing brought high-grade fiber adjacent to country rock.

No conclusive evidence was obtained to explain the origin of the delicately banded, fine-grained chrysotile that forms a few veins at Cassiar and almost invariably borders asbestos veins in partly serpentinized dunites and peridotites elsewhere in the area. The fine-grain of the chrysotile may reflect a rapid nucleation of material that first diffused into the veins. If this was the case at Cassiar the fine-grained material was, in most cases, completely recrystallized at a later time. An alternative suggestion is that this type of chrysotile formed when the temperature was relatively low, probably during the waning stages of asbestos growth.

Comparison of the Cassiar Serpentinite Body with Other Ultramafic Bodies in the Area.—None of the other ultramafic bodies in the area are as highly fractured as the serpentinite body at Cassiar. A study of joints in the McDame area reveals that the major factor influencing the density of fractures in volcanic and ultramafic rocks is the thickness of an individual body. The thick sills of volcanic rocks and large stocks of ultramafic rocks are much less jointed than the smaller bodies. The Cassiar serpentinite is one of the smallest ultramafic bodies in the area and this factor coupled with the structural position of the body on the limb of the synclinorium presumably determined the high density of fractures that were produced by deformation.

Most of the serpentinites in the area have undergone no significant metamorphism since they were formed. Northwest of Blue River, however, metamorphism has been more intense than that at Cassiar, and olivine has been regenerated from serpentinite. Much of the ultramafic rock in this area appears to have been little serpentinzed prior to metamorphism by the Cassiar granitic rocks. Perhaps the optimum conditions of metamorphism for asbestos growth are reached when feathery reticulated antigorite begins to replace mesh-structure chrysotile, serophite, and bastite.

CONCLUSIONS

The localization of high-grade asbestos at Cassiar appears to have resulted from an unique combination of serpentinization, fracturing and metamorphism. The ultramafic body was probably completely serpentinized prior to the emplacement of the Cassiar granitic rocks. The high density of fractures in

the asbestos deposit is related to the size of the body and to its structural position. Metamorphism and deformation probably accompanied the emplacement of the Cassiar granitic rocks. In this environment optimum conditions for the growth of chrysotile asbestos were reached.

ACKNOWLEDGMENTS

The writer is indebted to the management of Cassiar Asbestos Corporation, Limited, for facilitating work on the Cassiar Asbestos property. Much of the material in this report was included in a Ph.D. thesis submitted to Columbia University and the writer is grateful for the constructive advice and criticisms given by Professors C. H. Behre, Jr., W. H. Bucher, R. J. Holmes, P. F. Kerr and Arie Poldervaart.

REFERENCES

1. Bates, T. F., and Mink, J. F., 1950, Morphology and structure of the serpentine minerals antigorite and chrysotile: (abstract) Geol. Soc. America Bull., v. 61, p. 1442.
2. Cooke, H. C., 1937, Thetford, Disraeli, and eastern half of Warwick map-areas, Quebec: Geol. Survey, Canada, Mem. 211.
3. Gabrielse, H., 1955, Petrology and structure of the McDame ultramafic belt, British Columbia: Ph.D. thesis, Columbia University, University Microfilms Publ. 15,627, 141 p.
4. Kalousek, G. L., and Muttart, L. E., 1957, Studies on chrysotile and antigorite components of serpentine: Am. Mineralogist, v. 42, p. 1–22.
5. Riordon, P. H., 1955, The genesis of asbestos in ultramafic rocks: Econ. Geol., v. 50, p. 67–81.
6. Smitheringale, W. V., 1957, The mine of Cassiar Asbestos Corporation, Limited, Cassiar, B. C.: The Geology of Canadian Industrial Mineral Deposits, 6th Commonwealth Mining and Metallurgical Congress, p. 49–53.

Economic Geology
Vol. 55, 1960, pp. 338–353

THE DISCOVERY OF A COPPER-ZINC DEPOSIT AT GARON LAKE, QUEBEC

G. F. JOKLIK

CONTENTS

	PAGE
Abstract	338
Introduction	339
Regional geology—the choice of areas	341
Airborne geophysical survey	342
Fixed wing E.M. and magnetometer	342
Helicopter E.M.	343
Follow-up	
Ground geophysical survey	344
Diamond drilling	344
Geological setting of the copper-zinc deposit	346
Post-Keewatin intrusives	346
Keewatin meta-sediments and amphibolite	347
Structure	348
Mineralogy	350
Wallrock alteration	350
Acknowledgments	352
References	353

ABSTRACT

An exploration venture that led to the discovery of a small ore-grade copper deposit in the very active Mattagami Lake exploration area of northwestern Quebec is described.

The Garon Lake property was staked to cover a small, isolated E.M. anomaly that was recorded during an airborne survey of a folded post-Keewatin basic intrusion. A ground geophysical survey confirmed the presence of a narrow but good conductor, and of a coincident, positive magnetic anomaly. Diamond drilling has indicated the presence of a body of massive sulfides containing a little over 2% Cu.

The sulfide deposit is in a group of metamorphosed Keewatin lavas, tuffs, and sediments intruded by older gabbro, and by systems of late unmetamorphosed dikes, of which lamprophyre, olivine diabase, and albite granite, are examples. The strike and dip of the mineralization are essentially parallel to the strike and dip of the country rock. The shoot of massive sulfides plunges at about 60°. Pyrrhotite, pyrite, chalcopyrite, and sphalerite occur in varying proportions, and show textural evidence of having replaced the pre-existing rock.

The mineralization is near the contact between amphibolite (derived from lavas) and quartz-rich schist (derived from sediments). More particularly, the sulfide body is closely associated with an alteration aureole of cordierite-anthophyllite hornfels. Examples of base metal sulfide deposits that are structurally and genetically related to the formation of mag-

nesium-rich cordierite-bearing metasomatic zones have been described from other parts of the world. Geographically the closest described example is the Amulet ore body in the Noranda district. The discovery of this type of deposit on the Garon Lake property sheds new light on exploration in the Mattagami Lake area.

INTRODUCTION

Due to the discovery of several non-outcropping bodies of base metal-bearing sulfides, the country to the south and west of Mattagami Lake in northwestern Quebec has recently become the busiest prospecting territory in eastern Canada.

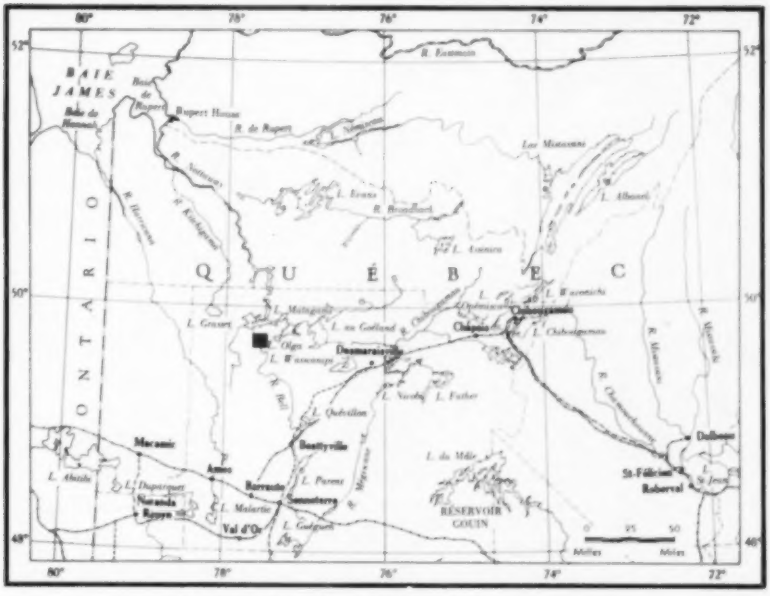


Fig. 1. Location of Garon Lake property.

The best known discoveries have been the Watson Lake, New Hosco and Orchan deposits (Fig. 2), at all of which surface diamond drilling is in progress.

The discoveries to date have resulted from the follow-up of airborne magnetic and electromagnetic surveys, which have been successful because of the massive structure of the mineralization and the common association of pyrrhotite and magnetite with the base metal sulfides. The deposits are covered by thick glacial overburden.

Although the diamond drilling of the Garon Lake deposit began only in the summer of 1958, the airborne geophysical surveys that led to the discovery were undertaken in the spring of 1956, at a time when general interest in the

new base metal province was still dormant. Isolated exploration ventures such as this now have blossomed forth into one of the most massive and refined drives in the history of base metal exploration. It is estimated that by the end of this year, most of the Keewatin greenstone province of northwestern Quebec and eastern Ontario, an area of about 20,000 square miles, will have been covered by the initial airborne geophysical survey and follow-up ground work.

FIG. 2. Geology of Mattagami Lake area (from Quebec Department of Mines Map 1257).

After the completion of the first exploratory drill holes on the Garon Lake property, a company was formed in which Conwest Exploration Company Limited became the major shareholder, with Kennco Explorations (Canada) Limited retaining a minor interest. The new company, named Garon Lake Mines Limited, continued diamond drilling and carried out a Turam electromagnetic survey of the whole property.

Diamond drilling has indicated a body of 295,000 tons of massive sulfides containing 2.12% Cu.

REGIONAL GEOLOGY—THE CHOICE OF AREAS

Little information on which to base the selection of areas for prospecting was available early in 1956. The aeromagnetic maps that have since been released by the Department of Mines and Technical Surveys have been of considerable help to the more recent participants in the "Mattagami rush."

The belt of Keewatin volcanic and sedimentary rocks that extends from Chibougamau westwards to and beyond the Ontario border is extensively intruded by granite and granodiorite. Bodies of basic rock, which have since been metamorphosed, were emplaced during a second period of intrusion. Finally, diabase dikes, which are unmetamorphosed, filled a system of faults that trends northeast, approximately parallel to the Grenville "Front."

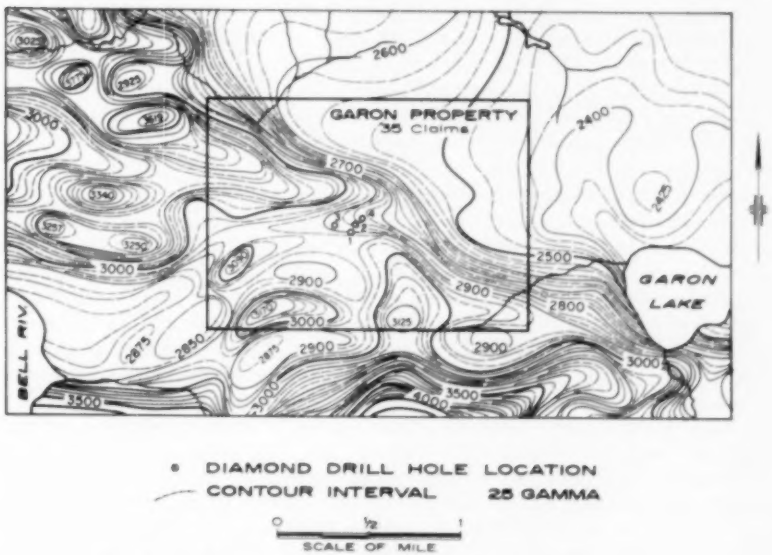


FIG. 3. Airborne magnetic survey of Garon Lake property.

The Chibougamau anorthosite and the Opemiska gabbro, both of which contain currently producing copper mines, are products of the second period of intrusion. Other, similar intrusions, such as the Bell River Complex, were chosen as starting places for a prospecting programme in the region.

The Bell River Complex (Fig. 2) outcrops as two masses over a length of forty miles and a width of ten miles, and intrudes a group of metamorphosed Keewatin lavas, tuffs and sediments that strike east-northeast. Although the complex has been mapped as a layered lopolith, the aeromagnetic compilation indicates that the structure is not simple. The strongly magnetic trends on Figure 3 represent some of the most northerly layers that are rich in magnetite.

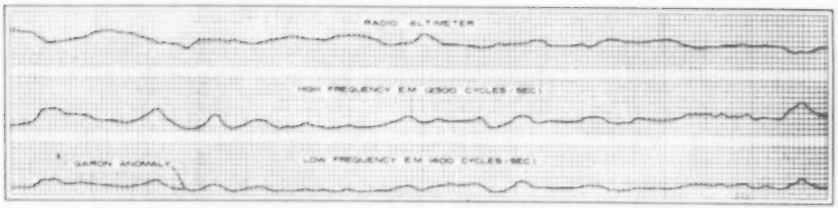


FIG. 4. Instrument tape showing airborne electromagnetic anomaly over Garon Lake copper-zinc deposit.

AIRBORNE GEOPHYSICAL SURVEY

Fixed Wing E.M. and Magnetometer.—The Bell River Complex was included in an area of 500 square miles that was selected for airborne geophysical survey. The work was contracted to Hunting Airborne Geophysics Ltd., who used a Canso aircraft fitted with a Gulf airborne magnetometer and with an electromagnetic system measuring phase shifts at frequencies of 400 and 2,300 cycles per second. The flight line spacing was 1,320 feet, and the average flying height 500 feet.

The resulting records reflected the effects of conductors in solid rocks, such as concentrations of massive sulfides, graphite and magnetite, and of surficial conductors, such as thick clay deposits, water-logged stream gravels, swamps, and bodies of saline water (Fig. 4). The ratio of the magnitude of the low frequency response to that of the high frequency response, and the degree of isolation of each anomaly were found to be the best criteria for distinguishing between the effects of surficial conductors, graphite- and magnetite-bearing shears, and massive sulfide deposits. That magnetite can cause anomalies of considerable size and of high ratio was shown during the follow-up of a one-line response in the northern portion of the Bell River Complex. High, coincident magnetic responses warned of such conditions but could, on the other hand, have indicated concentrations of magnetite in association with sulfide deposits such as the Watson Lake ore body. Graphitic zones were found to be difficult to discount since many sedimentary members of the Keewatin formations include beds that contain graphite as well as iron sulfides. Where, however, a conductive zone gave rise to anomalies on one flight line after another until it extended for a mile or more along the strike of the country rock, its quality in relation to possible base metal mineralization became suspect wherever pronounced variations in response ratio and no coincident magnetics were recorded. Although ore bodies a mile or more long are known, and some massive sulfide bodies do not cause aeromagnetic responses, copper deposits in the Keewatin of Quebec are generally much less than a mile long, and do give rise to aeromagnetic anomalies. Apart from such refinements, the strength of the dual frequency system appeared to be its applicability to the distinction between bedrock and surface conductors.

Although its low-frequency magnitude was only 0.2 degree out-of-phase, the response ratio of the anomaly recorded over the Garon Lake deposit isolated

it in profile (Fig. 4). The deposit was not reflected in the aeromagnetic contours (Fig. 3), but caused a sharp anomaly of 50 gamma on the instrument tape.

A field office was established at Val d'Or, the base from which the survey was carried out, instrument records were reduced as they were brought in by the aircraft, and staking crews were dispatched within a matter of days.

Helicopter E.M.—Several small E. M. anomalies, including the one under discussion, were staked only after a check by a second E.M. system mounted in a Bristol Sycamore helicopter. This instrument measured in-phase and out-of-phase responses at one frequency. Transmitting and receiving coils were towed at tree-top level in a large "bird."

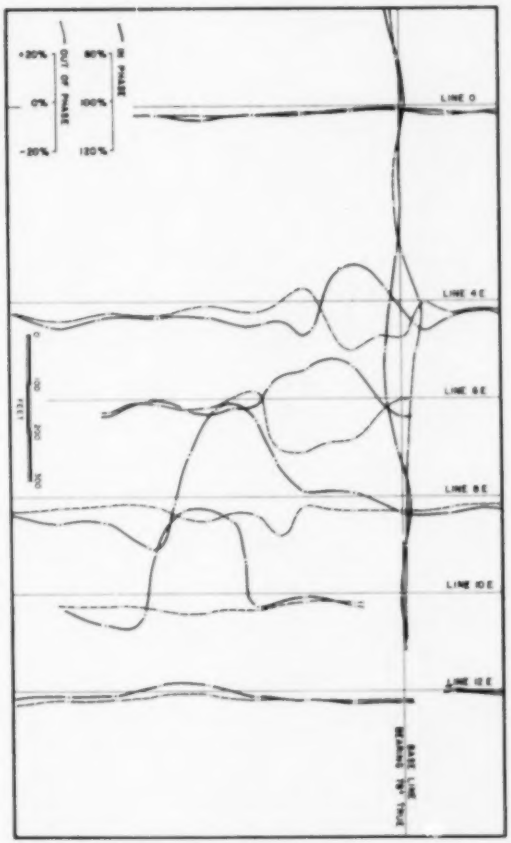


FIG. 5. Portion of ground E.M. (Ronka) survey over estimated position of airborne E.M. anomaly.

A grid of six lines, three north-south and three east-west spaced at 600 feet, was laid out over the estimated position of the fixed wing E.M. anomaly. Small but sharp positive anomalies appeared on the in-phase traces in the center of the grid. A group of 35 claims was staked around the anomalous ground.

FOLLOW-UP SURVEY

Ground Geophysical Survey.—The approximate position of the anomaly was located on the ground, and a grid totalling only two line miles was cut. The subsequent magnetometer and Ronka E.M. surveys were carried out by members of the Kennco exploration staff.

The Ronka unit utilizes two horizontal co-planar coils at a spacing of 200 feet, and measures the in-phase and out-of-phase responses at a frequency of 876 cycles per second. In-phase to out-of-phase ratios of up to 8:1, and responses typical of massive sulfides at shallow depth, were recorded on lines 8E and 10E. Somewhat poorer conductors were indicated on lines 4E and 6E (Fig. 5). To the east, the conductive zone showed up weakly on line 12E, and to the west it could be traced rather doubtfully across the base line to line 0. The total probable surface expression of this conductor, or series of conductors, was therefore 1,200 feet, but responses indicative of massive sulfides extended over only 200 feet. The thickness suggested by E.M. data was in all places less than 50 feet.

A magnetic anomaly which, on line 8E, rises to a peak of over 11,000 gama, was found to coincide with the conductive zone (Fig. 6).

Diamond Drilling.—The geophysical anomalies are on the southern slope of a wooded ridge 50 feet in height, and trend approximately east-west. The ridge is bordered to north and south by jack pine and alder swamps. Several outcrops near the crest suggest that the thickness of overburden is not great. A packsack drill was therefore moved to the property as soon as possible after the completion of the ground geophysical survey. Seven vertical holes totalling 195 feet were drilled before freeze-up with inconclusive results. The first hole (P 1, Fig. 6) included a length of 12 feet that assayed 1.30% Cu and 2.90% Zn. None of the other holes yielded as much encouragement. All intersection angles suggested an almost vertical dip for the mineralization and the host rock.

A large machine was moved to the Garon Lake property early in July 1958, to test the conductive zone by means of four holes, all of which were inclined at 45°.

Hole No. 1 was spotted to intersect the best ground E.M. and magnetic anomalies, which coincide on line 8E at 350 feet south of the base line. A core length of 75 feet, which straddles the contact between facies of essentially sedimentary and volcanic origin, is mineralized by disseminated pyrite, pyrrhotite, and very minor chalcopyrite and sphalerite. The sulfides form stringers in the schistosity planes of the host rock. The only mineralization of economic significance is a core length of 22 inches that assayed 3.77% Cu and 0.54% Zn.

Hole No. 2 was put down on a similar anomaly, but intersected 14.5 feet of massive sulfides at the contact of a cordierite-rich alteration zone. The

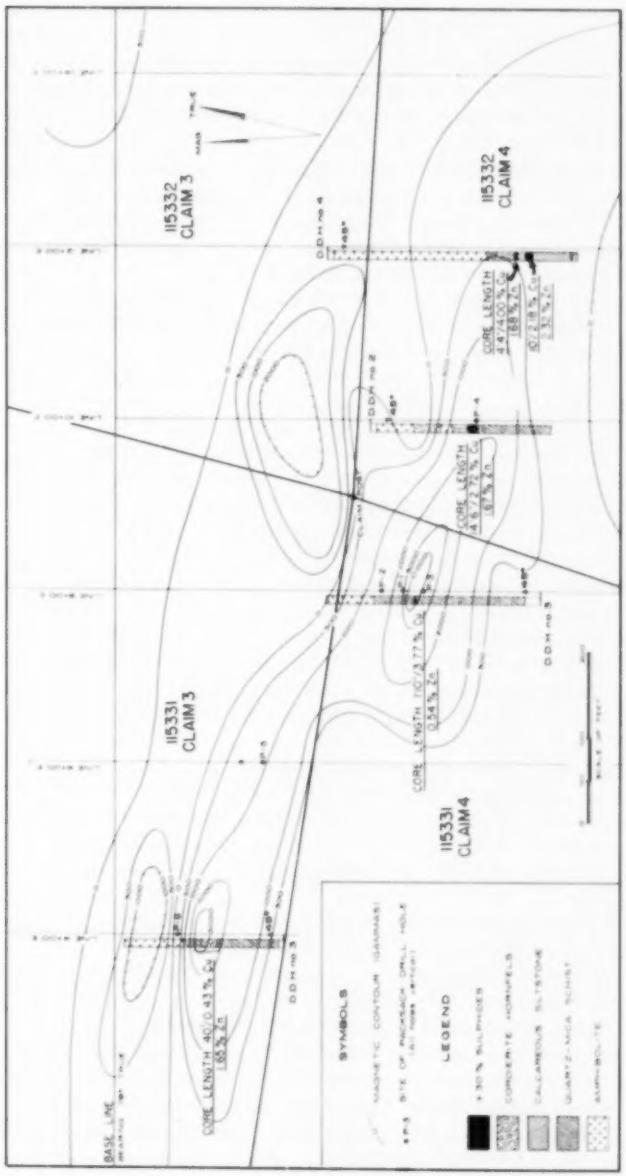


FIG. 6. Ground magnetometer survey and horizontal projection of diamond drill holes nos. 1 to 4.

sulfides averaged 2.72% Cu and 1.67% Zn. The grade improves appreciably from north to south.

Hole No. 3 tested the distinct, but somewhat poorer anomaly on line 4E. Here the mineralization is disseminated and confined to the cordierite-rich rock, which was once more intersected. A 40-foot core length assayed an average of 0.43% Cu and 1.65% Zn.

The results of Holes Nos. 1 and 2 suggested that the massive sulfide zone plunged east. Despite the weak geophysical responses on line 12E, *Hole No. 4* was drilled to test this theory. Two shoots of massive sulfides were intersected; a core length of 52 inches assayed 4.00% Cu and 1.68% Zn, and a core length of 10 feet averaged 2.18% Cu and 2.32% Zn.

The cost per foot of drilling was $7.45, the greater part of which represented the cost of transporting a machine and tractor by air from Senneterre to Rapid 10 on the Bell River, a distance of 100 miles.

GEOLOGICAL SETTING OF THE COPPER-ZINC DEPOSIT

The mineralization is in a group of metamorphosed Keewatin lavas, tuffs and sediments that strikes east-northeast, dips steeply, and is conformably intruded by the most northerly layers of the Bell River Complex. The petrological subdivision, which is given here, is based on a study of thin sections, most of which were prepared from drill cores.

Post-Keewatin Intrusives
- Lamprophyre
- Olivine diabase—Late Dikes
- Albite granite

Metamorphic Unconformity
- Meta-gabbro—Bell River Complex

Keewatin
- Quartz-mica schist, calcareous siltstone (meta-sediments)
- Quartzo-feldspathic hornblende schist (meta-tuff)
- Amphibolite (meta-basalt and meta-andesite)

Post-Keewatin Intrusives

Late Dikes.—Three systems of relatively unmetamorphosed dikes have been recognized on and near the Garon Lake property.

A dike of massive, light gray lamprophyre was intersected in the fourth diamond drill hole. Twinned, euhedral, zoned crystals of hornblende ($c^{\wedge}Z = 22°$) are set in a groundmass of pale green hornblende and andesine. Radiating crystals of epidote and interstitial grains of analcite form clusters that may be cavity fillings. Since all minerals are entirely fresh, the dike may be the latest intrusive in the area. Lamprophyres are not rare in the Keewatin province of northwestern Quebec (1). Dikes of olivine-rich lamprophyre were described by Watson (10) from the Bachelor Lake area, which is fifty miles east-southeast of Garon Lake.

Olivine diabase fills many of the great faults that cut the Keewatin rocks and parallel the Grenville "Front" for distances of up to 350 miles. At least one major dike cuts the older Precambrian rocks in a northeasterly direction at a distance of five miles northwest of Garon Lake (Fig. 2), and causes a positive magnetic linear. The texture of the rock is ophitic. Laths of basic andesine, 3 mm in average length, are oriented at random; the interstices are filled by fresh grains of olivine and titanaugite. Magnetite constitutes about 5 percent of the rock. Biotite, serpentine and apatite occur in accessory amounts.

Dikes, up to 30 feet wide, of massive, feldspar-rich granite were cut in diamond drill holes that were subsequently put down by Garon Lake Mines Ltd. on lines 13E and 14E. About half the rock is zoned plagioclase. Whereas the inner, presumably more calcic, portions of the crystals are partly altered, the sodic borders are fresh. Other minerals present are quartz, hornblende, and accessory apatite and magnetite. Albite granite was described from the Noranda-Amulet area by Wilson (11), and may be the latest phase of the widespread post-Keewatin granitization.

In places, dikes of olivine diabase were observed to cut across intrusions of albite granite.

Meta-Gabbro.—Some basic rock of the Bell River Complex outcrops in the western portion of the Garon Lake property. Most of the rock is coarse-grained and only faintly schistose. The predominant ferromagnesian mineral is fibrous, bluish-green hornblende ($c\hat{Z} = 22°$) which is probably derived from pyroxene. A small proportion of hornblende is altered to chlorite and magnetite. Plagioclase (An_{35}) is extensively altered to saussurite, and is partly recrystallized. The remainder of the rock consists of minor quantities of quartz, apatite, pyrite and magnetite. In places, the meta-gabbro is schistose, and is veined extensively by epidote, calcite, quartz, and scapolite. The amphibole is actinolitic ($c\hat{Z} = 18°$). Untwinned albite and epidote take the place of andesine. The outlines of the original plagioclase crystals are rarely visible. Apatite occurs in concentrations of up to 5 percent, which indicates some metasomatic activity.

Since its margins conform to the banding of the volcanic country-rock, and the intruded and intrusive rocks contain mineral assemblages of essentially the same metamorphic facies, the Bell River Complex was probably emplaced prior to the folding and metamorphism of the Keewatin rocks.

Keewatin Meta-Sediments and Amphibolite

The contact between hornblende-rich, quartz-poor rocks to the north, and quartz-rich, essentially micaceous rocks to the south, is intersected in diamond drill holes Nos. 1 to 4 (Fig. 6), and appears to have influenced the emplacement of the copper-zinc deposit. Since the average grain size of the rocks of these Keewatin formations is generally of the order of 0.05 mm, hardness and color are the only useful field characteristics for their identification; certainly all mineralogical determinations depend on thin section studies.

The schistose meta-sediments that outcrop in the southern part of the mineralized area are quartz-rich, mineralogically banded, and exceedingly fine-grained. They contain actinolite, chlorite, or one of the micas, as the principal aluminum- or magnesium-bearing mineral. Although the most common mineral associations are quartz-chlorite and quartz-actinolite, one horizon, which may be derived from graywacke, is characterized by the assemblages quartz-albite-chlorite, quartz-sericite-chlorite, quartz-sericite-biotite, and quartz-sericite-muscovite.

In drilling the fourth diamond drill hole, the massive sulfides gave way abruptly to exceedingly hard, fine-grained, grayish white calcareous siltstone. The rock consists of quartz (60 to 70%), plagioclase (10 to 20%), calcite (10 to 15%), and minor quantities of chlorite, sericite, ilmenite, magnetite and pyrite. Zones of discoloration or bleaching extend from pyrite-bearing veinlets of calcite. In this respect the siltstone resembles some horizons of the Devonian host-rock of the Gaspé copper ore bodies.

Hornblende-rich, quartz-poor rocks, for the most part amphibolite, outcrop in the northern and eastern portions of the mineralized area. The amphibole, which forms from 40 to 60 percent of the rock, is strongly pleochroic, bluish-green hornblende ($c\hat{}Z = 23°$). In most sections, hornblende shows pronounced preferred orientation, which defines the schistosity. The amphibolite formation is subdivided on the basis of the composition of the remainder of the rock.

In *andesine amphibolite* all minerals are recrystallized to form a granular texture. The grain-size, in contrast to that of some tuffaceous derivatives, is even. Plagioclase is commonly twinned, cloudy and partly altered to saussurite.

In *albite-epidote amphibolite*, plagioclase has been broken down by conversion of the anorthite molecule to epidote. The grain size of this rock is variable. Hornblende is partly altered to chlorite. Plagioclase is untwinned. Scapolite and other vein minerals occur in higher proportions than in andesine amphibolite.

Quartz-bearing amphibolite is distinctly banded and contains between 10 and 15 percent quartz. There are both andesine- and albite-epidote-bearing varieties which, in one case, alternate in the same specimen.

Of these three varieties of amphibolite, the first two are regarded as derivatives of basaltic and andesitic lavas; the third may be metamorphosed basaltic or andesitic tuff. In the drill cores, the bands of tuffaceous appearance are decidedly subordinate in quantity to the massive lavas.

STRUCTURE

Massive sulfides were intersected on lines 8E, 10E and 12E in DDH. 1, 2 and 4 (Fig. 6). In DDH. 1, a section of only 22 inches contains ore-grade copper mineralization. A core length of 14.5 feet of massive sulfides which was intersected in DDH. 2 is on the southern wall of an alteration zone of cordierite hornfels. The same rock was cut in DDH. 3 on line 4E, where it is

host to disseminated copper and zinc mineralization. In DDH. 4, on line 12E, the continuation of the massive sulfides was picked up as two separate veins, one of 4′ 4″, the other of 10′.

The strike of the shoot of massive sulfides is 5° S of E. The position of the intersection of disseminated sulfides on line 4E, and the trend of the magnetic anomaly, suggest that a drag-fold or a fault displaces the zone of mineralization between lines 8E and 4E. The strikes of isolated outcrops bear out the presence of a drag-fold.

The overall dip of the shoot of massive sulfides appears to be conformable with the steeply dipping schistosity and layering of the enclosing Keewatin rocks. Where the mineralization is disseminated, stringers of sulfides follow, and in no place transgress, the structure of the host rock. The peaks of the Ronka E.M. curves are in all cases almost vertically above the intersections of sulfides. The ground geophysical profiles on line 8E indicate a conductor that dips steeply south. On the other hand, a hole drilled by Garon Lake Mines Ltd. beneath DDH. 4 showed that between these two intersections, which are in the same vertical plane, the dip of the massive sulfide zone is 70° N.

The easterly plunge of the massive sulfide mineralization is proved by a consideration of the Ronka E.M. curves, and of the drill hole intersections on lines 8E, 10E and 12E. On line 8E, a response typical of massive sulfides was recorded at the surface, but DDH. 1 passed completely beneath the sulfide body. On line 10E, a similar response was validated by an intersection of the sulfide body. On line 12E, the E.M. profile indicates that massive sulfides are not present at the surface, but an intersection similar to that on line 10E was obtained at a vertical depth of 230 feet. The plunge to the east is probably about 60°.

The plunge of the zone of alteration is of interest. The positive magnetic anomaly, which appears to be due to the magnetite content of the cordierite hornfels, rather than to the pyrrhotite content of the sulfides, falls off gradually between lines 8E and 12E. The hornfels is probably at the bedrock surface on line 8E, but was missed, along with the major portion of the sulfide body, in DDH. 1. The rock was cut on line 10E, but was not seen in the core of DDH. 4 on line 12E. In the hole drilled by Garon Lake Mines Ltd. vertically beneath DDH. 4, the two sulfide veins united into one broad vein associated with cordierite hornfels. The zone of alteration therefore plunges conformably with the massive sulfides.

Since cordierite hornfels carrying appreciable disseminated mineralization was intersected on line 4E, the folding between lines 8E and 4E may be accompanied by a change in plunge of the sulfide and alteration zones.

Little evidence of shearing was seen in the drill cores. Although quartz grains are commonly strained, and the structure of the rock is in some places cataclastic, these phenomena are not restricted to the contact zones of the sulfide mineralization.

MINERALOGY

The massive sulfides intersected in DDH. 2 and 4 consist of pyrrhotite, pyrite, chalcopyrite and sphalerite. The gangue is quartz, chlorite and magnetite.

Pyrite, which is the major constituent of the sulfide zone in DDH. 4, is subordinate to pyrrhotite in DDH. 2. Most grains of pyrite are euhedral, and range in grain size from 0.3 to 3.00 mm. In the northern sulfide shoot, which was intersected in DDH. 4, there are both euhedral and anhedral grains of pyrite. Whereas euhedral grains are free of inclusions, quartz and chalcopyrite occur as inclusions in anhedral grains. In one specimen, pyrite includes quartz in a texture that resembles graphic intergrowth, but is probably to be interpreted as a replacement phenomenon.

Pyrrhotite forms anhedral grains that are commonly moulded onto euhedral pyrite crystals, and carry inclusions of quartz and pyrite. In some instances, pyrrhotite fills fractures in cracked grains of pyrite.

Chalcopyrite and *sphalerite* commonly display mutual boundaries, and are moulded onto pyrite. Both minerals, particularly sphalerite, contain inclusions of the iron sulfides, and are associated in fracture fillings of pyrite grains. Crystallographically oriented inclusions of chalcopyrite in sphalerite are abundant, and one example of the reverse phenomenon was seen.

Magnetite forms minute grains which, in most cases, show a preferred orientation.

Many stages in the replacement of the host rock by sulfides were observed. Fine-grained, feather-like aggregates of pyrite, pyrrhotite and chalcopyrite disrupt the fabric of grains of the silicate minerals, and sulfides commonly rim individual grains.

The order of deposition of the sulfide minerals may have been (1) pyrite, (2) pyrrhotite, (3) chalcopyrite and sphalerite. The criteria used to establish this order may be misleading since several cases were seen of euhedral pyrite crystals that appeared to have pushed aside previously formed grains of sulfides and gangue during their growth.

The disseminated sulfides in the cordierite hornfels intersected in DDH. 3 consist of pyrite, chalcopyrite and sphalerite. Sulfides are particularly abundant as "ghosts" of former aggregates of anthophyllite crystals, and in the planes along which cordierite is altered to sericite. Pyrite occurs as euhedral crystals free of inclusions, and as anhedral grains which contain inclusions of chalcopyrite and sphalerite.

WALLROCK ALTERATION

The cordierite hornfels that is adjacent to the body of massive sulfides in DDH. 2, and which carries the disseminated sulfide mineralization in DDH. 3, in hand specimen resembles a serpentinized basic igneous rock. The composition of this uncommon rock was determined by Prof. F. F. Osborne of Laval University.

The most abundant mineral is untwinned, optically positive cordierite that forms porphyroblasts up to 3 mm across. The porphyroblasts are riddled

by inclusions of practically all the other minerals present. Next in order of abundance are matted aggregates of chlorite, and radiating clusters of anthophyllite. Hercynite, a green spinel, occurs in knots, together with a small quantity of an undetermined mineral of high indices and birefringence. Quartz, pyrite and magnetite also occur. The structure of the rock is massive.

The degree of alteration of the hornfels varies. Some specimens are entirely fresh; in others, cordierite is altered to sericite, pinite, and to undefined isotropic aggregates. Anthophyllite is pseudomorphed by chloritic and talcose material. The extent of alteration of the rock is generally proportionate to its content of sulfides.

Where the metasomatic change of the original rock to a cordierite-anthophyllite-chlorite hornfels is not complete, patches of these minerals are seen to replace a quartz-biotite-sericite schist.

Cordierite is an anti-stress mineral that is generally found only in zones of contact metamorphism. The association of cordierite-bearing rocks with base metal-bearing sulfide deposits in regionally metamorphosed tracts has been described from several parts of the world:

(1) From *Orijärvi*, in Finland, P. Eskola (2) described the metasomatic transformation of quartzo-feldspathic derivatives of volcanic and pyroclastic rocks into cordierite-anthophyllite gneisses. At the same time, the local introduction of sulfides gave rise to copper sulfide ores. The Orijärvi granodiorite is regarded as the source of the agents of metasomatism and of the sulfides.

(2) According to Lindgren (4), the copper deposits at *Falun* and *Bersbo* in Sweden are also associated with cordierite-bearing gneiss. Both are considered to be high-temperature contact-metasomatic ore bodies.

(3) At the *Blue Hill* copper mines in Maine, Gillson and Williamson (3) described the conversion of quartz-chlorite schist into cordierite-anthophyllite-biotite hornfels by an intrusion of granite, which is also regarded as the source of the ores. The metasomatic change preceded the introduction of sulfides.

(4) Osborne (6) described the occurrence of the lead-zinc-silver deposit of *Calumet Mines, Limited* in gneisses of the Grenville Series. The wall zones contain cordierite and anthophyllite where the gneiss is non-calcareous; diopside and tremolite are developed where the environment is lime-rich. The same author (5) studied the almost identical occurrence of the lead-zinc ore body at the Tetreault Mine.

(5) The *Gull Pond* copper ore body in northwestern Newfoundland is in sheared Ordovician andesite or dacite lava. According to Snelgrove and Baird (8), cordierite is an especially characteristic and abundant gangue.

(6) At the *Amulet Mine*, four miles northwest of Noranda, copper-zinc-gold-silver ores are in Keewatin andesite and rhyolite. According to Price (7), the introduction of magnesium

> . . . has resulted in large areas of rocks being altered to cordierite-biotite-sericite and talc. These minerals tend to form a spotted maculose texture for which a local name "dalmatianite" or "dog" has come into general use. Later than this

general alteration is a cordierite-anthophyllite phase in which the anthophyllite needles form radiating clusters or rosettes. The local term of "Rad" has come into use for this type, which is closely associated with the orebodies as are much chlorite and clear porphyroblasts of cordierite.

ORIGIN

Facts that emerge from a study of thin and polished sections from the Garon Lake deposit are:

1. Cordierite-anthophyllite hornfels is formed by the alteration of quartz-biotite-sericite schist.
2. The hornfels is massive and has therefore been formed after the regional metamorphism of the Keewatin rocks and of the Bell River Complex.
3. The body of massive sulfides is closely associated with the zone of hornfels, which also is the host-rock of disseminated sulfide mineralization.
4. The sulfides were introduced contemporaneously with the alteration of the hornfels.

If the formation of the hornfels and the introduction of the sulfides were caused by closely related geological processes, which seems likely from the facts, a clue to the origin of the sulfides would be provided if the source of the magnesium that was added during the formation of cordierite and anthophyllite were known. Turner (9) says in this connection:

> It is possible . . . that dilute aqueous solutions of magnesium salts emanating from the cooling granite have caused insoluble silicates of magnesium to crystallize in place of silicates containing calcium or sodium, the corresponding calcic or sodic compounds having been more soluble than the magnesium salts under prevailing conditions of metasomatism. Petrologists who regard granites as products of metasomatism in place interpret basic (desilicated) contact zones of cordierite and anthophyllite rocks as "basic fronts" (magnesium fronts) enriched in magnesium expelled from the adjacent zone of granitization.

The occurrence of granite, which was intersected in drill holes on lines 13E and 14E, fits Turner's first interpretation. Alternatively, the second could be applied since the granitization of the fringe of the Bell River Complex, or of some later basic dikes, could provide ample magnesium (and copper).

ACKNOWLEDGMENTS

Permission to publish this paper was given by Conwest Exploration Ltd., Kennco Explorations (Canada) Ltd., and by Kennecott Copper Corporation. The manuscript was read by C. J. Sullivan and C. C. Kamm of Kennco, and by W. P. Hammond and M. Brown of Conwest.

Dr. F. F. Osborne of Laval University very kindly helped with some petrographic determinations.

Kennco Explorations (Canada) Limited,
1026 St. John St.,
Quebec, P. Q.,
June 8, 1959

REFERENCES

1. Cooke, H. C., James, W. F., and Mawdsley, J. B., 1931, Rouyn-Harricana region, Quebec: Geol. Survey Canada Mem. 166.
2. Eskola, P., 1914, On the petrology of the Orijärvi region: Comm. Géol. Finlande Bull. 40.
3. Gillson, J. L., and Williamson, R., 1929, Contact metamorphism of the Ellsworth Schist near Blue Hill, Maine: Econ. Geol., v. 24, p. 182–194.
4. Lindgren, W., 1933, Mineral Deposits, 4th Ed.: McGraw-Hill.
5. Osborne, F. F., 1939, The Montauban mineralized zone, Quebec: Econ. Geol., v. 34, p. 712–726.
6. ——, 1944, Calumet Island area: Quebec Dept. of Mines, Geol. Report 18.
7. Price, P., 1953, Waite Amulet Mines Ltd.: G.S.C., G.S.A. annual meeting, Guide Book for Field Trip no. 10, p. 18–20.
8. Snelgrove, A. K., and Baird, D. M., 1953, Mines and mineral resources of Newfoundland: Dept. of Mines and Resources, p. 46–47.
9. Turner, F. J., and Verhoogen, J., 1951, Igneous and Metamorphic Petrology: McGraw-Hill, p. 490.
10. Watson, K. D., 1955, Kimberlite at Bachelor Lake, Quebec: Am. Mineralogist, v. 40, p. 565–579.
11. Wilson, M. E., 1941, Noranda District, Quebec: Geol. Survey Canada Mem. 229.

Economic Geology
Vol. 55, 1960, pp. 354–362

SOME CATION SUBSTITUTIONS DURING THE FORMATION OF PHOSPHORITE FROM CALCITE[1]

L. L. AMES, JR.

CONTENTS

	PAGE
Abstract	354
Introduction	354
Methods of investigation	355
Results	356
Discussion	357
Summary	361
References	361

ABSTRACT

The nature of cation substitution during replacement of calcite by phosphorite allows the statistical treatment of data concerning such substitutions. Log-probability plots of data yield straight lines that allow easy and accurate extrapolations. Data are presented to show the effect of PO_4^{-3} concentration, temperature, flow rate, and Na^+ concentration on the primary inclusion of the radioisotopes of Pm^{+3}, Sr^{+2}, U^{VI}, and Pu^{IV}.

INTRODUCTION

Previous studies indicated that an apatite was formed by replacement of calcite in the presence of alkaline phosphate (PO_4^{-3}) solutions (3). It was further established that this replacement was probably the principal formational process of phosphorite deposits (2). During this process, it was found that substantial quantities of certain cations were removed from the influent solution into the forming apatite lattice. "Substitution" is a poor descriptive term for this inclusion process as it implies that a calcium ion already present in the apatite lattice is displaced to make room for an incoming cation of a radioisotope present in the influent solution. PO_4^{-3} replacement of CO_3^{-2} in calcite generates "vacant" cation sites that are filled either by an already-present Ca^{+2} or an incoming cation. The latter does not substitute for the former in the usual meaning of the word.

The wide range of cation substitutions allowed by the apatite structure has been known for some time but has received little attention in the laboratory. The occurrence of uranium in phosphorites has been adequately reviewed in the literature by McKelvey (8), McKelvey and Carswell (9), Davidson and Atkin (6), and Altschuler, Clarke, and Young (1). Altschuler et al. report general agreement that the uranium associated with phosphorites

[1] This work was performed under Atomic Energy Commission Contract No. W-31-109, Eng.-52.

is predominately an essential constituent of the apatite lattice. Their hypothesis is supported by the consistent relationship between fluorescent intensity and uranium content of the apatite, lack of admixed, identifiable uranium minerals, and inability to separate uranium physically or chemically from apatite constituents. These authors also noted a general lack of a universal correlation between P, F, CO_2, and U content. The question of the chemical form of uranium at the time of its incorporation into the apatite was not resolved but U^{IV} was favored (5).

Neuman et al. (11) demonstrated the ability of bone mineral (apatite) to remove UO_2^{+2} at near neutral pH. The adsorption of uranyl ion fell sharply, however, with a slight rise in pH and U concentration. The applicability of this equilibrium work to geological environs is open to question.

The presence of rare earths and strontium in apatite was reviewed by Palache et al. (12) and reported by McKeown and Klemic (10) and Borneman-Starinkevitch (4), Volodchenkova and Menentiev (14) and Borneman-Starinkevitch (4) proposed the substitution of Na^{+}-C^{+3} for $2Ca^{+2}$.

It is the purpose of this paper to report a laboratory study of some of these primary cation substitutions and their relationships to the variables phosphate concentration, temperature, flow rate, and in the case of the rare earths, Na^{+} concentration. From these kinetic relationships, it may be possible to gain a better understanding of how these variables effect the calcite replacement process, and to extrapolate from these experimental conditions to those of geological significance.

METHODS OF INVESTIGATION

The influent solutions of various compositions were passed through standard calcite columns (1.9 cm diameter × 12 cm long) as shown in Figure 1. Note that solutions were collected for radiochemical analysis immediately

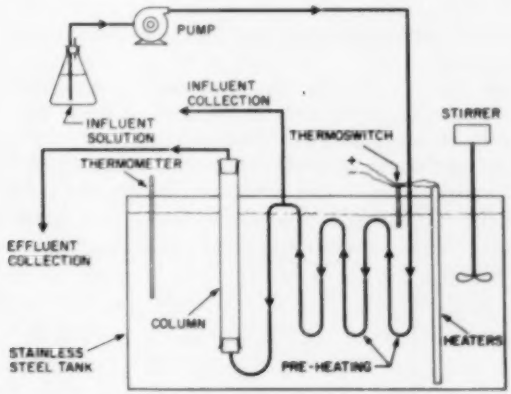


FIG. 1. Constant temperature apparatus.

before entering and immediately after leaving the calcite column. The pump used was a Lapp "Microflo" calibrated to deliver standard flow rates through the columns. Blade heaters in conjunction with a microswitch were used to maintain temperatures. Tygon or pyrex tubing was used throughout the flow circuit, and these were changed with each change in radiotracer. With changes in flow rates, a volume of influent equivalent to the volume of the pump plus tubing plus column was first passed through before sampling. Calcite columns were changed when PO_4^{-3} concentrations in the influent solutions were changed. The stainless steel Lapp pump was easily decontaminated with HNO_3 between runs.

Pm^{147} was utilized during this study as representative of the trivalent rare earths ($PmCl_3$), U as uranyl nitrate, and Sr^{90} and Pu^{239} were also nitrates. The Sr^{90} and Pm^{147} were obtained from Oak Ridge as spikes of high chemical purity. The U and Pu^{239} were Hanford products of like chemical purity.

All radiochemical analyses were by the Analytical Laboratories of the Hanford Laboratories Operation.

The surface area of the standard 0.25 to 1.0 mm calcite was determined to average 0.1 m^2/g by the standard B.E.T. N_2 adsorption method.

RESULTS

A linear plot of C/C_o vs. flow rate yielded a breakthrough curve analogous to that of an ion exchange column where throughput is plotted against C/C_o (C = effluent radioisotope concentration, C_o = influent radioisotope concentration). Here, however, the number of cation sites generated during calcite lattice rearrangement by PO_4^{-3} increases with decreasing influent solution flow rate. The number of cation sites generated per unit time, unlike the case of exchange resins, remains constant if calcite altering conditions remain constant (temperature, influent solution composition, flow rate, etc.). For this reason, flow rate may be used as a variable rather than column throughput. Another variable might have been chosen but flow rate proved to be the most convenient.

With an ion exchange column, the number of cation sites is fixed by the nature of the exchanger itself, and the number of these sites available for given incoming cations decreases as throughput increases. If a calcite column receives enough solution to approach complete exhaustion of the calcite this normal breakthrough curve is also obtained. In Figure 3, for example, for each point on the radioisotope removal line there is a breakthrough curve above and parallel to the ordinate represented by a straight line from this view.

Figure 2 illustrates this use of flow rate as a variable. A displaced breakthrough curve similar to that of an ion exchange material resulted (13). It is easily seen that had these breakthrough data resulted in a symmetrical curve, it would have represented a normal frequency distribution with $C/C_o = 0.5 = \overline{X}$ (7). In reality, however, this curve was skewed, which required that the data be presented in a log-probability rather than linear-probability

form to obtain a straight line. Figure 3 (25° C) is such a plot of the same data used in Figure 2.

The advantages of obtaining such a straight line will become apparent as these results are presented.

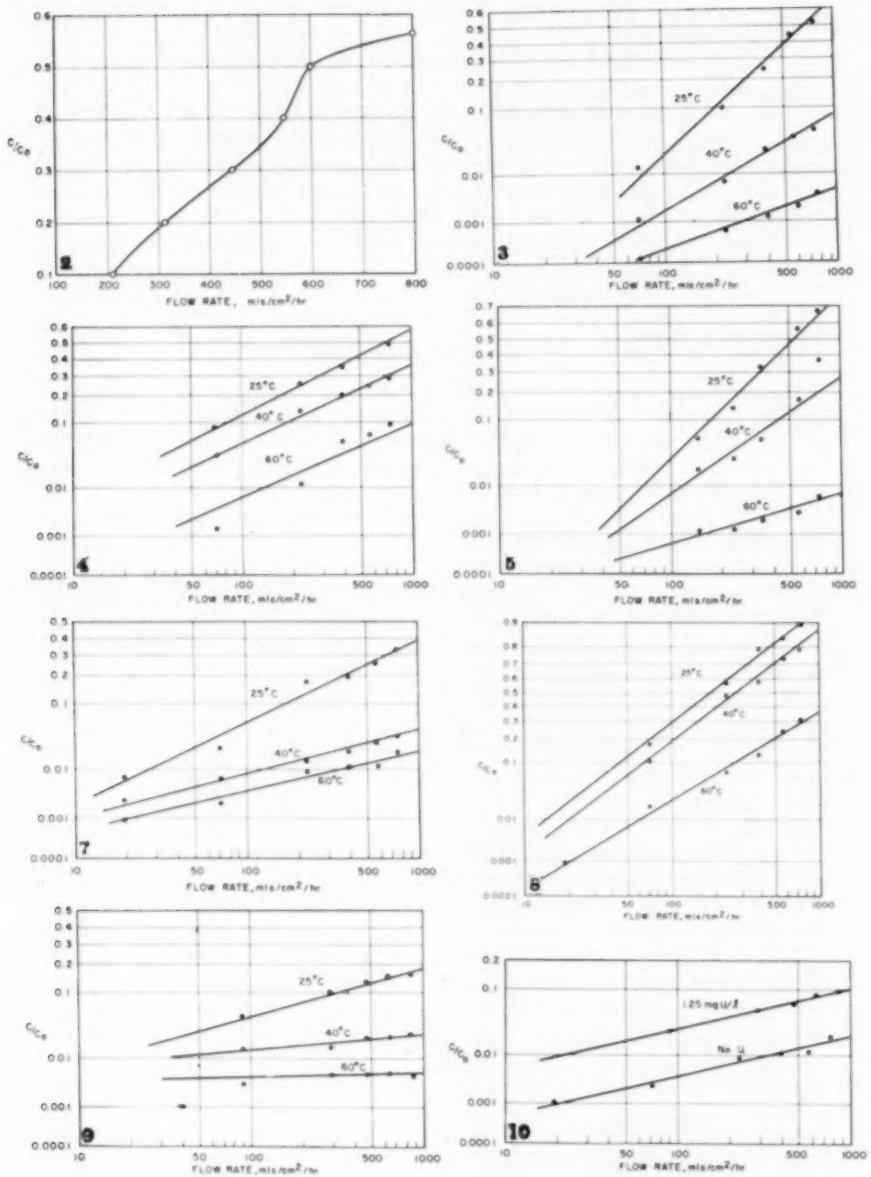
Figures 3 and 4 present Pu^{IV} removal data, Figures 5 and 6 show UO_2^{+2} removal, Figures 7, 8, 9, and 10 are concerned with Pm^{+3}, Figures 11 and 12 with Sr^{+2}, and Figure 13 is removal of PO_4^{-3}, under the respective experimental conditions listed. It should be emphasized that these data are valid and meaningful only for these experimental conditions. These removal data are corrected where removal of radioisotopes by adsorption on calcite is appreciable by subtraction of the portion of radioisotope so removed from the total amount removed.

DISCUSSION

From a consideration of these data with and without 1 *M* $NaNO_3$, it is obvious that these radioisotopes are not being removed by ion exchange on the resulting apatite. The author does not say that these ions do not show ion exchange phenomena with apatite under appropriate conditions, or that exchanges involving these ions and apatite are always unimportant. However, the primary inclusion of cations into the forming apatite lattice is as important a mechanism for the enrichment of apatites in strontium, uranium, and the rare earths as any other.

From a consideration of the chemical behavior of U in alkaline solutions, it is highly improbable that any uranium except UO_2^{+2} is being removed as shown in Figures 5 and 6. The Pu^{IV} removal as shown in Figures 3 and 4 is considerably different than that of U. If the U were being removed as U^{IV} rather than U^{VI}, Figures 3 and 4 should closely resemble Figures 5 and 6 since the sizes of Pu^{IV} and U^{IV} are nearly identical (0.86 and 0.89 kX respectively). It was previously determined that > 99 per cent Pu^{IV} was used here, and that the amount of PuO_2^{+2} in solution was insignificant under the experimental conditions. U^{IV} may also be removed on apatite by this reaction, but it is not necessary to postulate the formation of U^{IV} from U^{VI} before removal into the forming apatite as Altschuler et al. (1) have done.

The effect of $NaNO_3$ on radioisotope removal is seen to be most pronounced with Pm^{+3}. The addition of 1 *M* $NaNO_3$ is roughly equivalent, in number of additional cation sites generated, to increasing the PO_4^{-3} concentration to 0.1*M*. Although the number of sites do not actually increase with Na^+ addition (i.e., PO_4^{-3} removal does not increase), the number of available cation sites, in effect, does increase. Increases in temperature actually do increase the amount of PO_4^{-3} removed per unit time, and hence increase the number of cation sites. Note that the addition of competitive U considerably depressed Pm removal. This is probably due to the fact that coupled substitutions (Na^+-Pm^{+3} for $2Ca^{+2}$) are unnecessary with U, which gives U an advantage in competition with Pm for the fixed number of available cation sites. It is spacially more simple for a UO_2^{+2} than for Pm^{+3}-Na^+ to substitute for $2Ca^{+2}$. It is not easier for UO_2^{+2} to substitute for $2Ca^{+2}$ when in



FIGS. 2–5, 7–10.

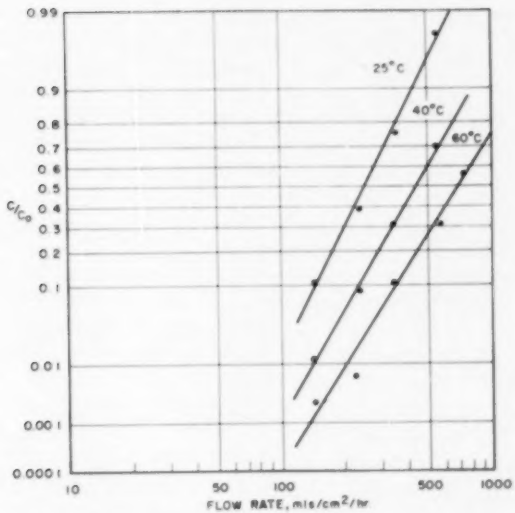


FIG. 6. Variation of UO_2^{+2} removal with flow rate and temperature. Influent solution: 0.005 *M* Na_3PO_4, 1.25 mg UO_2^{+2}/l, pH = 11.9. Column: 50 g, 0.25 to 1.0 mm calcite column.

competition with Ca^{+2} present in the influent solution. The presence of 1 *M* $NaNO_3$ has a depressing effect on Sr removal in terms of per cent Sr in the resulting apatite. Some Na^+ is normally required in the Ca^{+2} position but large quantities can compete with Sr^{+2}.

FIG. 2. A typical "breakthrough" curve.

FIG. 3. Variation of Pu^{239} removal with flow rate and temperature. Influent solution: 0.05 *M* Na_3PO_4, 0.13 mg/l Pu^{IV}, pH = 11.9. Column: 50 g, 0.25 to 1.0 mm calcite.

FIG. 4. Variation of Pu^{239} removal with flow rate and temperature. Influent solution: 0.005 *M* Na_3PO_4, 0.13 mg/l Pu^{IV}, pH = 11.9. Column: 50 g, 0.25 to 1.0 mm calcite.

FIG. 5. Variation of UO_2^{+2} removal with flow rate and temperature. Influent solution: 0.05 *M* Na_3PO_4, 1.25 mg/l UO_2^{+2}, pH = 11.9. Column: 50 g, 0.25 to 1.0 mm calcite.

FIG. 7. Variation of Pm^{147} removal with flow rate and temperature. Influent solution: 0.05 *M* Na_3PO_4, 2.87×10^{-6} mg/l Pm^{+3}, pH = 11.8. Column: 50 g, 0.25 to 1.0 mm calcite.

FIG. 8. Variation of Pm^{147} removal with flow rate and temperature. Influent solution: 0.005 *M* Na_3PO_4, 2.87×10^{-6} mg/l Pm^{+3}, pH = 11.8. Column: 50 g, 0.25 to 1.0 mm calcite.

FIG. 9. Variation of Pm^{147} removal with flow rate and temperature. Influent solution: 0.005 *M* Na_3PO_4, 1 *M* $NaNO_3$, 2.87×10^{-6} mg/l Pm^{+3}, pH = 11.9. Column: 50 g, 0.25 to 1.0 mm calcite.

FIG. 10. Variation of Pm^{147} removal with flow rate and competitive UO_2^{+2}. Influent solution: 0.05 *M* Na_3PO_4, 2.87×10^{-6} mg/l Pm^{+3}, 60° C, pH = 11.9. Column: 50 g, 0.25 to 1.0 mm calcite.

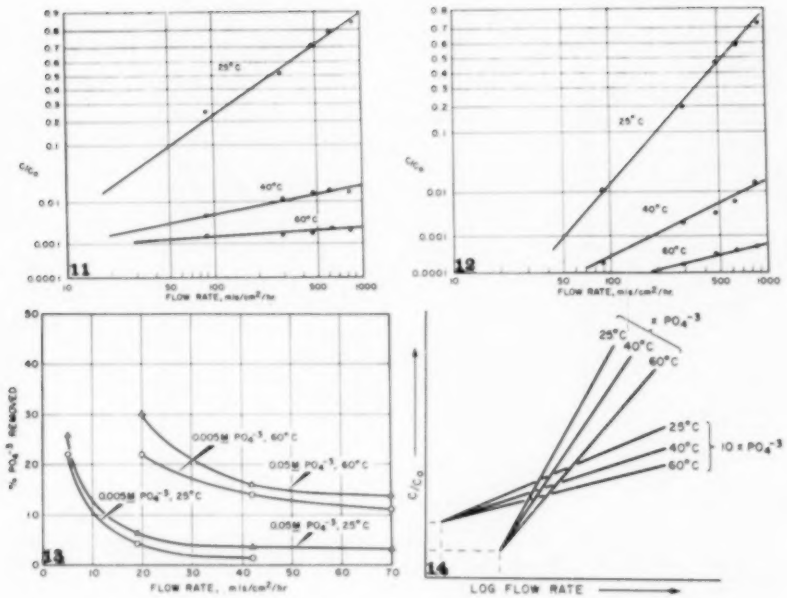


FIG. 11. Variation of Sr^{90} removal with flow rate and temperature. Influent solution: 0.05 *M* Na_3PO_4, 1.5×10^{-4} mg/1 Sr^{90}, pH = 11.8. Column: 50 g, 0.25 to 1.0 mm calcite.

FIG. 12. Variation of Sr^{90} removal with flow rate and temperature. Influent solution: 0.05 *M* Na_3PO_4, 1 *M* $NaNO_3$, 1.5×10^{-4} mg/1 Sr^{90}, pH = 11.9. Column: 50 g. 0.25 to 1.0 mm calcite.

FIG. 13. Variation of PO_4^{-3} removal with flow rate and temperature. Influent solution: Na_3PO_4 concentration as indicated, 100,000 d/m/ml P^{32}, pH = 11.8. Column: 50 g, 0.25 to 1.0 mm calcite.

FIG. 14. Generalized radioisotope removal diagram.

It is also apparent that these radioisotope removal lines at the various temperatures and for a given PO_4^{-3} concentration will meet at a single point, or nearly so, within experimental error. This point represents that flow rate below which temperature variations between 0° and 100° at one atmosphere pressure no longer affect the rate of radioisotope removal. (This point results because cation removal does not keep pace with PO_4^{-3} removal increases.) One would always expect to find such a point whose positon varies with calcite grain size as well as with PO_4^{-3} concentration and temperature.

Figure 14 shows the generalized relationships between these removal lines for a given cation. As Figure 13 shows, the actual weight of PO_4^{-3} removed per unit volume of influent solution is much greater with the 0.05 *M* PO_4^{-3} than with the 0.005 *M* PO_4^{-3}, or the number of cation sites being generated per unit time is much greater in the former case than in the latter. The per

cent PO_4^{-3} removed should theoretically be the same for both concentrations. As the rate of production of these cation sites increases the proportion of cations extracted is unable to keep pace, as shown by the fact that the lines representing 0.005 *M* PO_4^{-3} intersect at lower C/C_o values than with the 0.05 PO_4^{-3}. The production of cation sites is so much greater at the latter concentration that the rate of diffusion of appropriate cations to these sites is not rapid enough to cause an increase in cation extraction commensurate with that of PO_4^{-3}.

Thus one may increase the per cent Sr, U, or Pm in the resulting apatite, all other things being equal, by decreasing the PO_4^{-3} concentration and flow rate, or increasing the concentration of given cation present in the influent solution. In the latter case the C/C_o remains the same unless the Ksp for the corresponding phosphate is exceeded. A high Ca to Sr, Pm, or U ratio tends to decrease the amount of U, Sr, or Pm appearing in the resulting apatite, more so in some combinations than in others. The presence of 1 ppm Ca^{+2}, for example, depresses the 60° C line for Sr^{+2} removal in Figure 4 to approximately that at 40° C. Any of these cations present in the original calcite would, of course, be retained in the resulting apatite.

It is obvious that much work remains to be done on primary cation substitutions, not to mention anion substitutions, in apatites. For example, the author has altered phosphorites to fluorite with 0.01 *M* NaF solutions from pH 2 to 11 at room temperature. With alkaline to neutral solutions, calcite is directly altered to fluorite in the absence of PO_4^{-3}; Sr, U, Pm, and Pu are likewise included during this replacement.

However complex the system, the experimental and data treatment methods demonstrated in this paper are adequate to outline system parameters.

SUMMARY

A study is presented of the effect of temperature, PO_4^{-3} concentration, flow rate, and Na^+ concentration on the inclusion of U^{VI}, Pu^{IV}, Pm^{+3} and Sr^{+2} during replacement of calcite with apatite. The fraction of cations removed is not proportional to the fraction of PO_4^{-3} removed, i.e., increases in PO_4^{-3} removed do not necessarily cause proportional increases in the increment of cations removed. The substitution Na^+-Pm^{+3} for $2Ca^{+2}$, and of UO_2^{+2} for $2Ca^{+2}$, is confirmed by implication. The method of investigation and data treatment are of general value for other studies of this kind.

General Electric Company,
Richland, Washington,
July 16, 1959

REFERENCES

1. Altschuler, Z. S., Clarke, Jr., R. S., and Young, E. J., 1958, Geochemistry of uranium in apatite and phosphorite: U. S. Geol. Survey Prof. Paper 314-D.
2. Ames, L. L., Jr., 1959, The genesis of carbonate apatites: Econ. Geol., v. 54, no. 5, p. 829–840.

3. Ames, L. L., Jr., McHenry, J. R., and Honstead, J. F., 1958, The removal of strontium from wastes by a calcite-phosphate mechanism: A.E.C. Publication A/CONF. 15/P/395, U.S.A.
4. Borneman-Starinkevitch, I. D., 1938, On some isomorphic substitutions in apatite: Acad. Sci. U.S.S.R., Comptes rendus (Doklady), v. 19, no. 4, p. 253–255.
5. Clarke, R. S., Jr., and Altschuler, Z. S., 1958, Determination of the oxidation state of uranium in apatite and phosphorite deposits: Geochim. et Cosmochim. Acta, v. 13, p. 127–142.
6. Davidson, C. F., and Atkin, D., 1953, On the occurrence of uranium in phosphate rock: Internat. Geol. Cong., Algiers, Comptes rendus, Sec. 11, fasc. 11, p. 13–31.
7. Gore, W. L., 1949, Statistical Methods for Chemical Experimentation: Interscience Manual 1, p. 17.
8. McKelvey, V. E., 1956, Uranium in phosphate rock: U. S. Geol. Survey Prof. Paper 300, p. 477–481.
9. McKelvey, V. E., and Carswell, L. D., 1956, Uranium in the phosphoria formation: U. S. Geol. Survey Prof. Paper 300, p. 483–487.
10. McKeown, F. A., and Klemic, H., 1956, Rare-earth-bearing apatite at Mineville, Essex County, New York: U. S. Geol. Survey Bull. 1046-B, p. 9–23.
11. Neuman, W. F., Neuman, M. W., Main, E. R., and Mulyran, B. J., 1949, The deposition of uranium in bone, VI. Ion competition studies: Jour. Biol. Chemistry, v. 179, p. 341–348.
12. Palache, C., Berman, H., and Frondel, C., 1951, Dana's System of Mineralogy, II: p. 877–878.
13. Rhodes, D. W., and Nelson, J. L., 1957, Disposal of radioactive liquid wastes from the uranium recovery plant: U. S. A.E.C. Publication HW-54721 (UNCLASSIFIED), p. 11–12.
14. Volodchenkova, A. I., and Melentiev, B. N., 1943, Apatites of two textural types from apatite-nepheline rocks of chibiny: Acad. Sci U.S.S.R., Comptes rendus (Doklady), v. 39, no. 1, p. 34–35.

Economic Geology
Vol. 55, 1960, pp. 363-382

PRIMARY MINERALIZATION OF URANIUM-BEARING "SILICEOUS REEF" VEINS IN THE BOULDER BATHOLITH, MONTANA: PART II—THE VEINS[1]

BARRIE H. BIELER AND HAROLD D. WRIGHT

CONTENTS

Part II

Abstract 363
The veins 364
Mineralogy 364
Coloration of the vein quartz 367
Texture of vein quartz 370
Vein paragenesis 371
Radioactivity and texture 374
Uranium content 375
Trace element content and vein color 377
Relationship of uranium content to some trace elements 379
Summary 379
Acknowledgments 380
References 381

ABSTRACT

The "siliceous reef" uraniferous veins of the Boulder batholith contain, in decreasing order of abundance, finely crystallized pyrite, sphalerite, galena, uraninite, tetrahedrite, argentite, chalcopyrite, and covellite. Microcrystalline quartz comprises over 90 percent of the vein material; opal and barite are minor. The color of the veins varies from light gray to black due to variation in size and concentration of the microscopic grains of opaque minerals.

Microcrystalline quartz was deposited in several stages, separated by intervals of brecciation. Quartz of the later stages is generally dark gray to black. It occurs as fracture fillings in massive early microcrystalline quartz of light color, and as a cementing matrix about breccia fragments of the lighter quartz.

The uranium content of nearly one hundred vein samples was determined by alpha counting and fluorimetry. Radioactive equilibrium of the uranium series is indicated by agreement between measured radium content (analyzed by New Brunswick Laboratory, AEC) and that required for equilibrium with uranium determined in two samples, and by general agreement between fluorimetric and alpha-activity determinations of uranium. Semi-quantitative spectrographic analysis of the same samples

[1] Contribution No. 58-118 from the College of Mineral Industries, The Pennsylvania State University, University Park, Pa. This paper represents a portion of the Ph.D. dissertation of Barrie H. Bieler, "Primary Uranium Mineralization in Some Hydrothermal Vein Deposits in the Boulder Batholith, Montana," The Pennsylvania State University, 1955.

provided data on the content and distribution of 28 minor elements in the veins. In most cases, the darker the vein quartz, the higher is the content of those elements generally occurring in opaque vein minerals: Ag, As, Ba, Co, Cu, Fe, Mn, Mo, Ni, Pb, Sb, Sn, U and Zn. Elements that showed no significant correlation with vein color are Al, B, Be, Ca, Cr, Cs, Ga, Ge, Mg, Na, P, Sr, Ti, V, and Zr. Five elements—Fe, As, Co, Mo, and Pb—showed a marked positive correlation with uranium.

THE VEINS

Mineralogy

The vein minerals are discussed in four groups: silica minerals, sulfide minerals, uranium minerals, and "others."

Silica Minerals.—Studies of the microcrystalline vein quartz and the opal were made with the aid of optical, electron microscope and X-ray techniques.

All samples of vein quartz were found to have $n_o = 1.544$, matching the

TABLE 3

ESTIMATED GRAIN SIZE DISTRIBUTION* IN MICROCRYSTALLINE VEIN QUARTZ COLOR GROUPS, OPAL, CLAY, AND OPAQUE INCLUSIONS; AND ESTIMATED VOLUME PERCENTAGES OF CLAY AND OPAQUE INCLUSIONS IN MICROCRYSTALLINE QUARTZ

Color of microcrystalline quartz		Grain diameter, μ				Sericitic clay inclusions					Opaque inclusions					
						Diameter, μ		% volume			Diameter, μ			% volume		
		< 3	3–10	10–20	> 20	< 10	> 10	< 1	1–5	5–15	< 5	5–10	> 10	< 1	1–5	> 5
Light gray	13**	10	35	40	15	75	25	60	25	15	65	25	10	50	50	0
Tan to brown	10	10	45	40	5	55	45	50	50	0	60	35	5	35	50	15
Gray	18	10	35	45	10	65	35	70	20	10	60	30	10	65	30	5
Dark gray	18	15	45	30	10	70	30	85	15	0	85	15	0	5	55	40
Black	9	25	45	30	few	75	25	50	50	0	80	20	0	10	15	75
Quartz, undifferentiated	68	15	40	35	10	70	30	65	30	5	70	25	5	35	40	25
Opal	3	100	0	0	0	100	0	100	0	0	100‡	0	0	0	100	0

* In parts per 100.
** Number of samples in each group.
‡ Submicroscopic limonite (?).
Notes: (1) Individual grains of microcrystalline quartz are closely interlocking and generally equant (1:1 to 1:1 1/2) to slightly elongate (1:2-3) in section.
(2) Opaque inclusions vary in shape from nearly spherical to acicular, platy, or irregular, and occur singly or in clusters.

standard value for quartz. Table 3 presents a summary of data on the size and shape of vein quartz grains and the amount of included clays and opaque minerals in the various color classes of quartz. Most of the vein quartz in all color classes falls in the range of about three to twenty microns. Sericite in plates and shards is intimately mixed with the quartz. Although accurate estimates of the percentage volume of opaque inclusions are difficult to make, there appears to be some correlation between the concentration of inclusions and the color of the vein quartz, with higher concentrations in the darker shades of quartz. Most of the opaque inclusions are less than five microns

in diameter, and the size range is thus appreciably smaller than that of the quartz.

Four electron micrographs of the quartz are shown in Figure 2. A texture resembling that of novaculite is observed on the broken surfaces of vein quartz. Step-like fracture surfaces are commonly seen, and these may represent the rhombohedral cleavage of quartz (Fig. 2a). Approximately hexagonal outlines, suggesting euhedral quartz crystals, are more rarely observed (Fig. 2b). In some samples, plates interpreted as clay inclusions, some with hexagonal outlines, intersect the rough surface of the quartz (Fig. 2c).

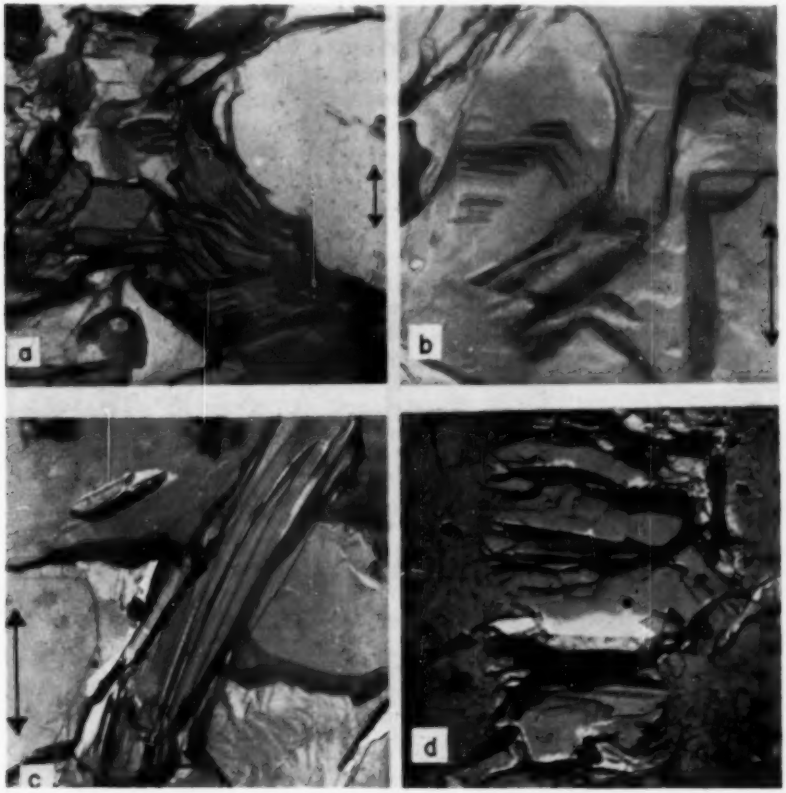


FIG. 2. Electron micrographs of carbon replicas of four microcrystalline quartz samples; arrow represents one micron. 2a. Broken surface showing irregular and step-like fracture surface. Magnified 9,000 ×. 2b. Angular outlines of quartz crystals on natural fracture surface. Magnified 16,000 ×. 2c. Plates of clay (?) intersecting fracture surface of quartz. Magnified 16,000 ×. 2d. Fracture surface showing quartz crystals engulfed by opal. Magnified 7,000 ×.

The ochre-colored opal was found to have a refractive index varying from 1.41 to 1.44. Fine crystals of quartz in the opal are commonly observed under the microscope. An electron micrograph, Figure 2d, shows a pattern interpreted as representing opal enveloping quartz crystals. X-ray diffractometer patterns of two opal samples showed them to be composed chiefly of tridymite, but reflections indicating amounts of both low and high cristobalite also were present. Grinding of the sample may cause inversion of low cristobalite to the high form (F. H. Gillery, oral communication). C. V. Raman (18), in optical and X-ray tests on several samples of hyalite and precious opal, concluded that his samples consisted of interlayered low and high cristobalite, with water present in scattered submicroscopic inclusions.

Sulfide Minerals.—Seven sulfide and sulfosalt minerals were identified in samples of vein quartz from the W. Wilson, G. Washington, and Free Enterprise mines, and five of these are present in the "base metal" type deposit at the Lone Eagle mine. The sulfides and sulfosalts in the three "reef" deposits are, in order of abundance, pyrite, sphalerite, galena, tetrahedrite, argentite, chalcopyrite, and covellite. Molybdenite occurs in a few pegmatites but was not found in the quartz veins. Samples from the Lone Eagle veins contain pyrite, chalcopyrite, sphalerite, galena, and argentite. Except in a few places where the sulfides occur in crystals several millimeters across, these minerals are scattered through the vein quartz of the "reef" deposits in discrete, generally anhedral grains of microscopic size.

Pyrite is the most abundant sulfide in all of the mines. The microscopic crystals are generally equant, subhedral to anhedral, and grade in size downward to the most abundant size range of 1 to 20 microns. Although most of the inclusions in this range cannot be identified, it is thought that a great majority are pyrite from the high iron content in the spectrographic analyses and from the fact that most of the inclusions at the large end of the range are pyrite.

Sphalerite occurs in irregular anhedral grains rarely in contact with other sulfides. The size range parallels that of pyrite. Sphalerite has replaced uraninite rather extensively and some grains show the outlines characteristic of blebs of uraninite. Due to the translucency as well as the fine grain size, sphalerite is not recognizable macroscopically in the vein quartz.

Galena is the only sulfide other than pyrite recognizable in the field, but is much less abundant. It occurs in the microcrystalline quartz in equant, subhedral to anhedral grains, or in thin veinlets rarely containing other sulfides. Tetrahedrite is found in scattered locations in the W. Wilson veins, and is characterized by relatively large anhedral grains surrounded by quartz. In a few places it was found in fine veinlets with galena.

Argentite occurs locally in both the W. Wilson and Free Enterprise mines, generally in anhedral blebs of relatively large size isolated from the other sulfides. The identification was confirmed by X-ray powder patterns made from material gouged from polished sections. Chalcopyrite and covellite were identified only in the polished sections from the W. Wilson mine.

Uranium Minerals.—Uraninite appears to be the only primary uranium mineral in these deposits. A well developed suite of secondary uranium min-

erals has been formed in the three "siliceous reef" deposits by the action of groundwater. The study of these minerals has been described elsewhere (6, 33).

Like the sulfides, uraninite is scattered through the micro-crystalline quartz in fine inclusions ranging down to unidentifiable grains in the few micron size range. The larger grains are of irregular shape, generally embayed, or are ring-shaped or rounded-elongate in section. These shapes suggest filling of irregular spaces between quartz grains, or coatings in the case of the rings. Less commonly uraninite is observed as thin coatings on fracture surfaces, or in thin plates arranged in a lacework texture. Rarely, lustrous black blebs of uraninite up to an inch across are encountered, but during three summers of field work uraninite was identified in place in only two locations in the W. Wilson mine.

Four samples of lustrous black uraninite were used for a measurement of the unit cell dimension from X-ray powder patterns. An internal standard of NaCl was used in each exposure to enable correction for film shrinkage. All visible lines were measured, the number measured appearing in parentheses following the computed average cell edge length: sample No. 1—5.39 Å (2), sample No. 2—5.41 Å (8), sample No. 3—5.41 Å (7), sample No. 4—5.46 Å (4).

Other Minerals.—Barite occurs in colorless, lath-like crystals in about 10 percent of the specimens from "siliceous reef" deposits. It is found in massive, medium gray vein quartz, and commonly shows etched crystal faces. All stages of replacement by quartz are represented. The crystals are small, generally 0.1 to 2 mm long. Spectrographic analysis of one sample of barite from the W. Wilson mine showed only about 0.1 percent strontium.

Limonite is rather abundant in all of the mines investigated. The limonitic clay in open fractures is undoubtedly related to oxidation in the vadose zone, but limonite is mentioned here because it is believed to be a pigmenting medium in parts of the "siliceous reef" veins. Most of the vein material in the white to black range is without hue. In the remainder, the hue ranges from pale buff to dark brown through shades of yellow or red brown. Red coloration, as might be caused by hematite, is rare. The pigmentation is commonly distributed quite uniformly through the vein quartz and opal.

Coloration of the Vein Quartz

There appeared to be two possible causes of the gray to black color of the "siliceous reef" vein quartz: (1) pigmentation by numerous small opaque inclusions, and (2) darkening by radiation from uranium and its daughters.

Color by Irradiation.—Frondel (7) has shown that colorless quartz can be made smoky by irradiation with X-rays, alpha particles, beta particles, gamma rays, deuterons, or an electron beam. By heating at 180° C the color is very slowly removed from artificial smoky quartz, and at about 300° C only a few hours of heating are required to remove the smoky color. Heating natural smoky quartz at somewhat higher temperatures makes it colorless.

The following experiments were made to evaluate the possible coloring effect of irradiation on several samples of "siliceous reef" vein quartz. Four specimens of vein quartz and two of opal were subjected to unfiltered copper X-radiation for exposure periods ranging between ¼ and 38 hours. The treatment produced pale gray to dark gray coloration of the exposed portion. The vein specimens were then broken in half across the circular exposed area, and one half of each heated for several hours. Specimens of smoky quartz, amethyst, citrine, and rose quartz were similarly heated. The dark irradiated spots on the vein quartz specimens disappeared on heating, but by comparison with the unheated fragments it was evident that the non-irradiated portions of the heated specimens did not change color. The amethyst specimen turned citrine, the smoky quartz colorless and the rose quartz and citrine somewhat paler in color.

It was concluded that irradiation of the vein quartz by the uranium series radioisotopes in the fine inclusions of uraninite is not an important factor in the dark gray and black coloration.

Color by Opaque Inclusions.—Unfortunately, the hypothesis of pigmentation by opaque inclusions is not subject to testing by simple experiment. However, fairly conclusive evidence was found in the course of microscopic studies of the vein material. Three-quarters of the black vein quartz samples examined contain an estimated five percent or more opaque inclusions, but somewhat less than half of the dark gray quartz samples contain more than five percent inclusions. Progressively smaller concentrations of inclusions were observed in the medium and light gray vein quartz (Table 3). Thin sections of vein material revealed the same trend, but quantitative estimates could not be made because of the difficulty of correlating shade of gray in hand specimens with specific portions of corresponding thin sections, with the fine textures involved. Under the electron microscope, vein quartz samples failed to show a "spotted" texture of opaque inclusions in quartz fragments ranging from one-tenth to two microns in diameter. The absence of such a texture suggests that few of the opaque inclusions are less than ¼ micron in diameter.

Identification of the opaque inclusions in polished sections was found to be possible only at the large end of the size range. Irregular grains of pyrite, galena, sphalerite, tetrahedrite, uraninite, and argentite were identified, but the identifiable grains represent only a small fraction of the total. Estimates of relative abundance of the minerals making up the inclusions were not possible.

Further evidence of the pigmentation role of the opaque inclusions was provided by semi-quantitative spectrographic analyses, discussed in a later section. In most cases, the darker the vein quartz, the higher the content of those elements commonly occurring in vein deposits in the form of opaque minerals; those present in the "siliceous reef" deposits are Ag, As, Co, Fe, Mo, Ni, Pb, Sb, U, and Zn. Elements that showed no apparent correlation with vein color are Al, B, Be, Ca, Cr, Cs, Ga, Ge, Mg, Na, P, Sr, Ti, V, and Zr. Most of the elements in the latter group occur chiefly in non-opaque minerals.

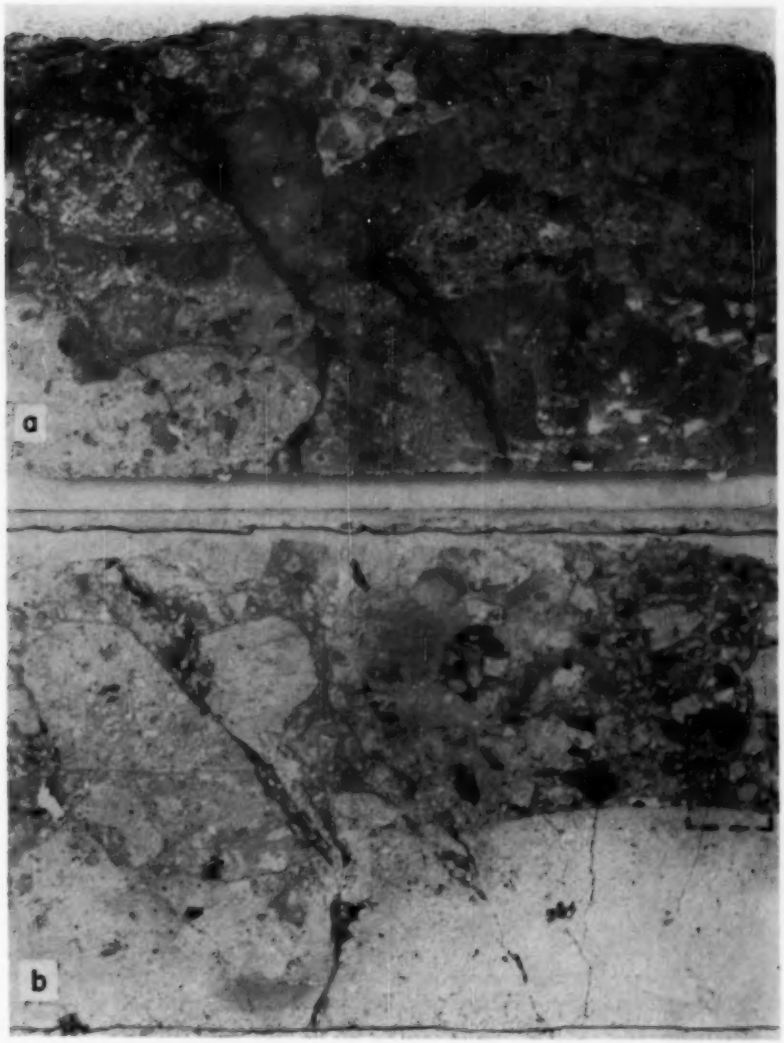


FIG. 3. Characteristic breccia and vein textures in microcrystalline vein quartz. Polished slab, one by one and one-half inches, with thin section adjacent to slab. 3a. Fragments of brownish gray microcrystalline quartz and silicified wall rock cemented by gray silicified fault gouge. The two dark veinlets are black microcrystalline quartz. 3b. Thin section. Dark areas in the breccia contain limonite. The fields covered in Figures 4 and 5 are shown by the large and small rectangles.

Meschter (14) showed evidence of microscopic sulfide mineral grains in the W. Wilson quartz veins; he found a small amount of sulfur in analyses of the dark gray vein quartz, and suggested that it was in the form of minute sulfide grains, which could explain the dark color. It should be pointed out that the small size, as well as the concentration, of the opaque mineral inclusions is an important factor in the pigmentation. Several volume percent of opaque minerals in grains greatly larger than five microns probably would not appreciably darken thin pieces of milky or light gray quartz gangue, although the transmissivity would of course be lowered.

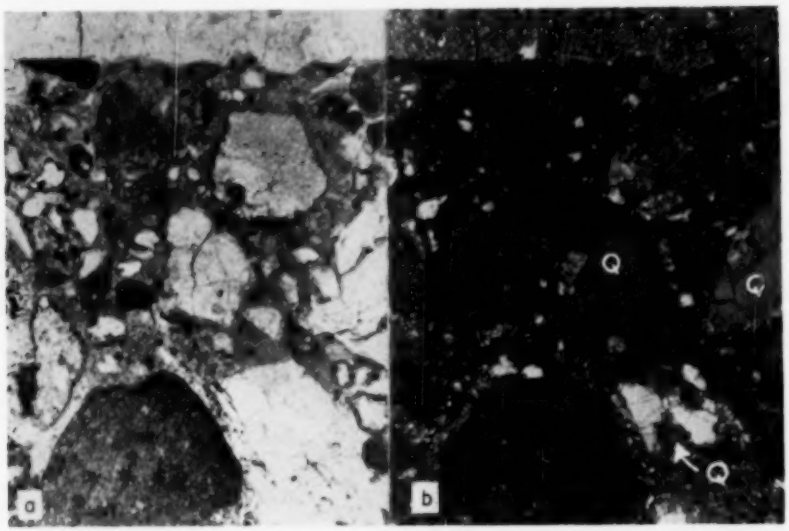


FIG. 4. Photomicrographs of thin section in Figure 3b. 4a. Detail of a breccia-microcrystalline quartz contact; much of the opaque material is limonite. Plane light, magnified 15 ×. 4b. Same field with nicols crossed at 80°. Note the quartz grains (Q) derived from the wall rock, some showing replacement by microcrystalline vein quartz. Magnified 15 ×.

Texture of Vein Quartz

Slabs of vein material remaining from preparation of thin sections were useful for studying vein texture and paragenesis, for correlation of microscopic texture with vein color, and for preparation of autoradiographs. The slabs were ground flat and coated with clear laquer for observation under a low power binocular microscope. About 130 specimens were studied in this manner. Some of the textural relationships are illustrated by the specimen described below.

A polished slab and its adjoining thin section are shown in Figure 3a, b. The central and lower right portions of this specimen illustrate the massive,

brown-stained medium gray vein quartz; smaller fragments of the same quartz appear in the lower left and upper right corners, cemented by light gray silicified gouge. The trapezoid-shaped fragment just below the upper left corner is a piece of silicified wall rock in which remnant fragments of quartz and orthoclase are visible. The latest stage of mineralization in the specimen is represented by the two black veinlets extending upward from the bottom of the picture and grading into the dark quartz cementing the breccia in the upper left.

The portion of the specimen outlined by the rectangle at the right edge of Figure 3b is shown at higher magnification in Figure 4. Part of the breccia is shown in Figure 4b, magnified about 10 times. Relatively large fragments of wall rock quartz ("Q") are seen; one of these (lower right) shows partial replacement by fine-grained vein quartz. The fine grain size of the gray vein quartz is apparent along the upper edge of the figure. Detail in the left-hand black veinlet, Figure 3, is shown in Figure 5 at a magnification of about 60 ×. The black fracture filling passes into a cement about the breccia fragments in the upper half of the picture.

A typical contact between light and dark gray vein quartz is shown in Figure 6, a photomicrograph of another sample at about 400 × magnification. Most of the inclusions are less than ten, and many less than five microns in diameter. Some of the larger inclusions are actually clusters of smaller ones, or represent superimposed inclusions scattered through the 30 micron thickness of the section.

Vein Paragenesis

The variety of textural relationships exhibited by the variously colored microcrystalline quartz enabled an interpretation of the sequence of quartz deposition in the vein. With the few percent of opaque minerals, we were not so fortunate—most of the individual mineral grains are surrounded by microcrystalline quartz and hence isolated from each other. Little textural evidence is afforded for interpreting the sequence of sulfide deposition. The manner in which these minerals occur in the microcrystalline quartz indicates that they crystallized contemporaneously with the quartz in any given stage. The spectrochemical analyses show roughly the same relative composition of metals in each of the major color varieties, which indicates that the same group of sulfides formed repeatedly, perhaps even continuously, during the filling of the veins.

"Siliceous Reefs."—The interpretation of the overall paragenesis of the veins in the three "siliceous reef" deposits is summarized in Figure 7. Although minor differences were observed, the similarity in major features is more striking. All three deposits are characterized by repeated intervals of major fracturing and brecciation, accompanied or followed by extensive deposition of microcrystalline quartz. Five such periods were recognized in the W. Wilson deposit, and four in the G. Washington and Free Enterprise deposits. All stages of fracturing and deposition may not be represented in the samples, and no special significance is attached to the particular number

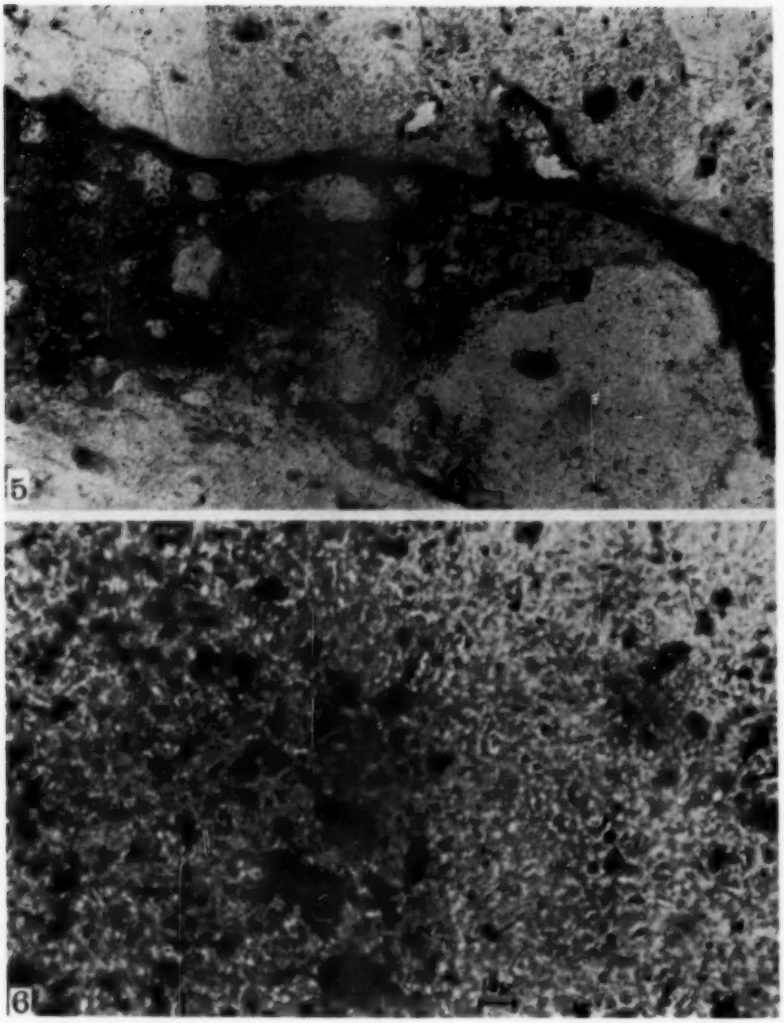


FIG. 5. Photomicrograph showing textural detail in a black microcrystalline quartz veinlet in Figure 3b. Note the breccia texture and the abundance of opaque inclusions. Plane light, × 80.

FIG. 6. Photomicrograph showing opaque inclusions in microcrystalline quartz, and detail of a contact between light and dark gray microcrystalline quartz. Note the difference in abundance of inclusions across contact. Plane light, × 380.

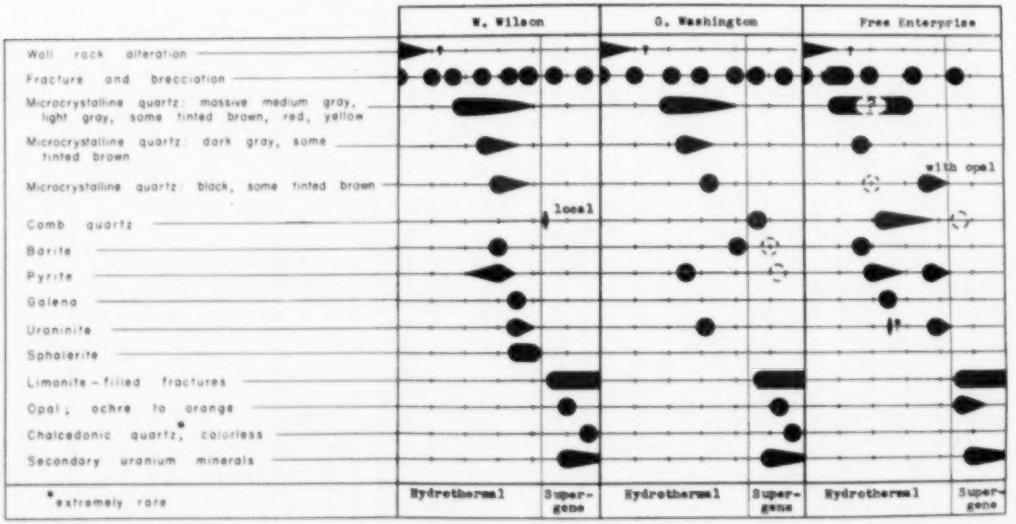


FIG. 7. Interpretation of vein paragenesis in the W. Wilson, G. Washington, and Free Enterprise deposits.

observed. They indicate a complex history of repeated cycles of fracturing and quartz deposition.

In all of the "siliceous reefs" the deposition of massive light to medium gray vein quartz accompanied and followed the silicification of the vein walls, and persisted throughout most or all of the interval of vein filling, although the amount diminished with time. Dark gray vein quartz was introduced during or after the second period of fracturing (the third period in the W. Wilson deposit), forming a lamellar structure, inter-leaved with earlier massive light to medium gray quartz. The next period of fracturing was followed by more local deposition of black, extremely fine-grained quartz, accompanied by more abundant base metal sulfides and uraninite as microscopic inclusions. Small concentrations of uraninite, pyrite, and galena were deposited with the black quartz. This stage represented the final hydrothermal activity.

Subsequent fracturing and brecciation provided the loci for deposition of secondary uranium minerals, aragonite, iron oxides, and hyalite opal by circulating groundwater. Although the evidence is not conclusive, the ochre-colored opal found in the three "siliceous reefs" is also believed to have had a supergene origin. The color suggests inclusions of hydrous iron oxides, which are abundant in the zone of oxidation above the water table, and all observed veinlets of ochre-colored opal transect the quartz veins. However, this opal was not associated with hyalite opal or any other conclusively secondary minerals.

Coarse Sulfides.—Specimens containing more concentrated and coarse-grained sulfides and uraninite than found in the normal siliceous vein material were obtained from a few scattered locations in the "siliceous reefs." The close association with black vein quartz appears to date them with the sulfide and uraninite inclusions of the latest period of quartz deposition, and the textural relationships of the coarse sulfides provided indirect evidence of the sulfide paragenesis in this quartz stage. The pyrite in these samples preceded all other sulfide minerals. After local brecciation, uraninite, galena, and tetrahedrite were deposited contemporaneously, accompanied and followed by sphalerite.

Radioactivity and Texture

The location and distribution of radioactivity in the vein samples was studied on a macroscopic scale with the aid of beta-gamma autoradiographs and on a microscopic scale by the use of alpha autoradiographs. The "slabs" used in the vein texture studies were exposed for periods of 8, 16, 32, and 64 days depending upon the activity in the specimen. Photographs of the vein "slabs" and their autoradiographs were enlarged five times and compared with a magnifying stereoscope. About 120 samples were studied and the results are tabulated in the appendix.

In the least radioactive group of samples about one-third of all the limonite-bearing veinlets and gouge areas have relatively strong radioactivity. Approximately one-tenth of the altered feldspar grains and many of the opal veinlets are radioactive. Essentially all of the activity in the above sites is

believed to be due to the presence of secondary uranium minerals. There appears to be a concentration of activity in the dark gray and black vein quartz as compared with the light and medium gray. About half of the samples of dark quartz revealed little or no activity, while in the lighter shades of vein quartz a vast majority of the samples are relatively non-radioactive.

The observations of samples in the more strongly radioactive groups are fewer in number, so less conclusive, but some trends are apparent. The higher the general level of activity in the sample, the greater is the proportion of black vein quartz which is highly radioactive. Limonite-filled veinlets and gouge are strongly radioactive in most cases.

On a microscopic scale there appear to be two possible loci for uranium in the vein quartz, exclusive of secondary uranium minerals: either in some of the small opaque inclusions, or as submicroscopic particles absorbed on grain boundaries in the vein quartz. Alpha autoradiographs were prepared with the same group of samples used for the beta-gamma autoradiographs, with exposures of 10, 20, 40, and 80 days. Nearly every group of alpha tracks could be traced to an opaque mineral grain, a crystal of a yellow-green secondary uarnium mineral, or a limonite-stained fracture. These observations indicate that the chief source of activity in fresh primary vein material is in some of the opaque inclusions. The larger grains are identifiable under the microscope as uraninite and it seems highly probable that the radioactive opaque inclusions which are too small to identify also are uraninite.

Uranium Content

Analysis for uranium in samples of the several color classes of vein quartz was made by fluorimetry, and equivalent uranium determinations were provided by alpha-counting; the two independent methods provided a mutual check. The radioactive equilibrium state in two samples of vein quartz was checked by fluorimetric uranium and radon-count radium determinations provided by the Atomic Energy Commission's New Brunswick Laboratory.

Techniques.—Due to the ubiquity of secondary uranium minerals, very careful preparation of vein samples was required for determination of primary uranium content. The samples were ground to 60 to 120 mesh and then hand-picked under a binocular microscope to exclude all grains that were iron-stained, off color, or contained visible particles of secondary uranium minerals. A fraction of generally 20 to 25 milligrams (depending upon availability of material) was ground and deposited from a n-butyl alcohol slurry onto a stainless steel disk one inch in diameter. The samples varied in thickness from 2 to 5 mg/cm^2, but most were between 3 and 4 mg/cm^2. This amount is intermediate between thin and thick sources of quartz. It was not practical to prepare enough material for a thick source, and uniform thin sources of this material could not be made. Absorption curves were used to calculate the expectable thick source count rate from the measured count rate. Standardization was achieved with four samples of uraninite in dunite of 0.001, 0.02, 0.1 and 2.85 percent uranium, prepared by the U. S.

National Bureau of Standards. The count rate from each standard was converted to that expected from the same uranium series content in quartz using absorption coefficients calculated from the Bragg-Kleeman rule (15). The instrumentation used was that described by Kulp et al. (13). Total counts were selected to give a standard counting precision of 2 to 5 percent (depending on sample activity) with one standard deviation.

Fluorimetric determinations were made on five milligram samples using a procedure modified from Grimaldi et al. (8, p. 6–7). The precision of the method was estimated to be about 5 to 10 percent for samples with more than 0.01% U and 10 to 20 percent for samples with less uranium. Determinations by the two methods differ by more than a factor of two for only seven of the 61 samples. To evaluate the degree of correlation between results of the two methods a scatter diagram was plotted on a log scale (Fig. 8). Two regression equations were calculated, each passing through the point $\bar{\alpha}$, $\bar{f}$ ($\bar{\alpha} = -2.043$, $\bar{f} = -2.035$). The equation of "f" as a function of "α" has the values $a = 0.1449$, $b = 1.0670$, (solid line, Fig. 8) that of "α" as a function of "f", $a = -0.2063$, $b = 0.9026$ (thin dashed line, fig. 8). The correlation coefficient "r" is 0.98, indicating that the probability of the two variables being independent is only one chance in more than 10,000. A "t" test for the values "a" and "b" in the equation $f = a + b$ ($a = 0.1449$, $b = 1.0670$) shows that "a" differs significantly from zero and "b" differs significantly from 1.0 (values for the equation $\alpha = f$).

These tests show that the alpha count and fluorimetric uranium determinations are in good agreement considering the low concentration level and the possibility of disequilibrium in a few samples. However, there is a consistent bias in one or both techniques: the alpha determinations are generally higher than the fluorimetric for low ($< 0.01\%$) uranium content, but are generally lower than the fluorimetric for higher ($> 0.01\%$) uranium content. The scatter of points appears to be greater for low uranium content than for high, reflecting the lower precision of both methods in this range. These results show that the samples analyzed could not be greatly out of radioactive equilibrium, and provide indirect evidence that the uranium in the samples is predominantly in the primary form rather than in secondary minerals due to redistribution by groundwater activity.

Of the two vein quartz samples submitted to the New Brunswick Laboratory, AEC, one was reported to contain 0.13% U and 4.3×10^{-10} g. Ra/g. sample. Calculation from the decay constants for U^{238} and Ra^{226} shows that 4.4×10^{-10} g. Ra/g. sample should be present with 0.13% U at equilibrium. The other sample contained 0.26% U, and 9.0×10^{-10} g. Ra/g. sample, as compared with the calculated equilibrium value of 8.8×10^{-10} g. Ra/g. rock. The analyses indicate that the distribution of uranium series elements in fine particles of uraninite, tightly locked in a quartz matrix, has not been greatly disturbed. They also support the rather crude visual evidence that recently deposited uranium in secondary minerals and in limonite in the gray fine-grained vein quartz is minor.

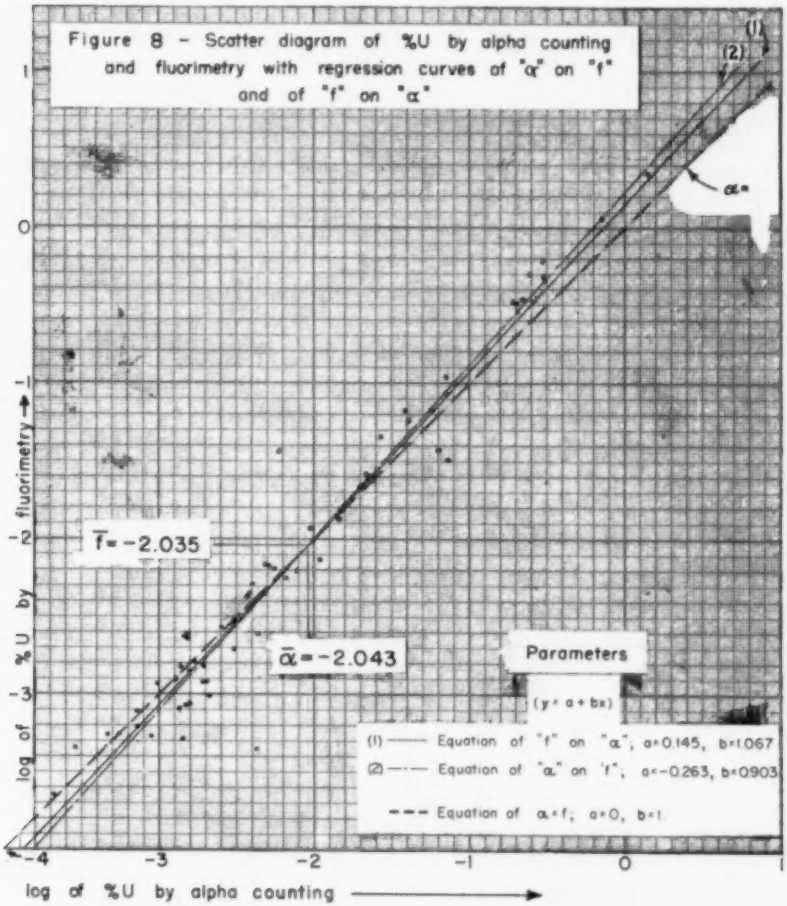


Figure 8 – Scatter diagram of %U by alpha counting and fluorimetry with regression curves of "α" on "f" and of "f" on "α"
(1)
(2)
α=f
$\bar{f}$ = -2.035
$\bar{\alpha}$ = -2.043
Parameters
(y = a + bx)
(1) —— Equation of "f" on "α"; a=0.145, b=1.067
(2) —·— Equation of "α" on "f"; a=-0.263, b=0.903
--- Equation of α=f; a=0, b=1
log of %U by fluorimetry
log of %U by alpha counting
1
0
-1
-2
-3
-4

Trace Element Content and Vein Color

A semi-quantitative spectrographic analysis for trace elements was made on a group of 83 samples of vein quartz. A 5 milligram split of each sample prepared for uranium determinations was analyzed. The exposure and development of the plates was handled by Dr. Harold Lovell and his staff in the Spectrographic Laboratories of the College of Mineral Industries, The Pennsylvania State University, and the plates were read by the senior author.

The determinations of 28 elements, in addition to uranium, in 50 samples of vein quartz are presented graphically in Figure 9 to show relationships with

vein color. The samples represent light gray, medium gray, dark gray and black vein quartz from the W. Wilson, G. Washington, and Free Enterprise mines. The correlation of elements with vein quartz color is shown in two groups: (1) those in which there is an apparent positive relationship between increasing element content and darker color, and (2) those with weak or no apparent correlation. In the first group are those elements generally occurring in opaque vein minerals; they are Ag, As, Ba, Co, Cu, Fe, Mn, Mo, Ni, Pb, Sb, Sn, U (by alpha count), and Zn. In the second group are Al, B, Be, Ca, Cr, Cs, Ga, Ge, Mg, Na, P, Sr, Ti, V, and Zr. As is to be

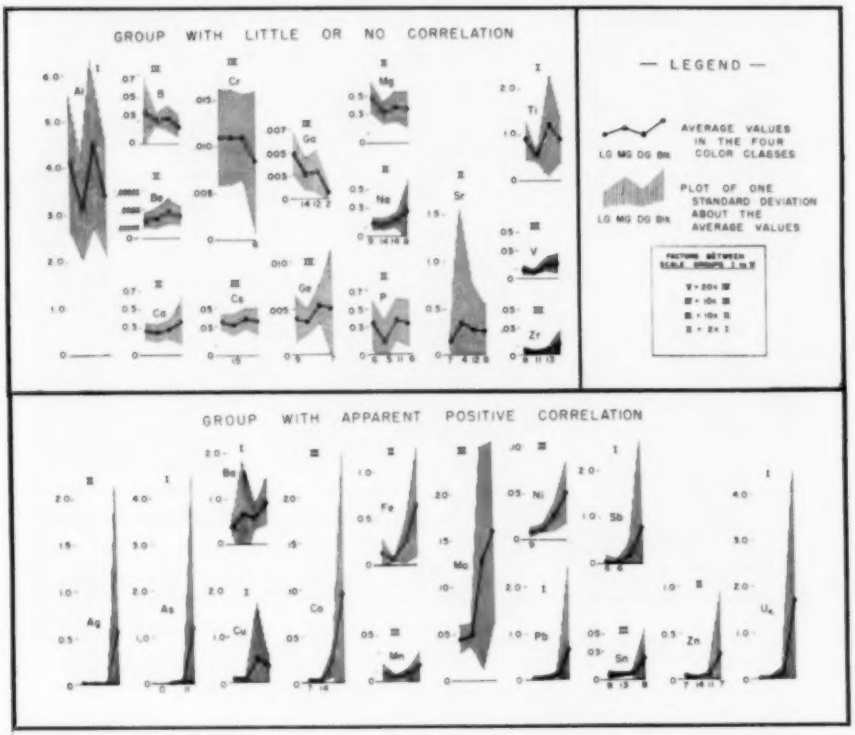

GROUP WITH LITTLE OR NO CORRELATION
— LEGEND —
AVERAGE VALUES IN THE FOUR COLOR CLASSES
LG MG DG Blk
PLOT OF ONE STANDARD DEVIATION ABOUT THE AVERAGE VALUES
LG MG DG Blk
GROUP WITH APPARENT POSITIVE CORRELATION

FIG. 9. Plot of trace element content vs. color classes and uranium content vs. color classes for 50 microcrystalline quartz samples from the W. Wilson, G. Washington, and Free Enterprise mines. The four color classes, light gray, medium gray, dark gray, and black, are plotted from left to right along the abscissa. The trace element content is plotted along the ordinate on a linear scale which varies for the different elements. The number of samples in the four color classes are 10, 16, 15, and 9, respectively. An element "not detected" in a certain color class is given the value zero for calculation of the average and the standard deviation. In such cases the number of samples in which the element was detected is indicated by the number below the abscissa.

expected the latter group represents elements generally occurring in non-opaque minerals. Two, boron and gallium, appear to have a negative correlation with quartz vein color.

Relationship of Uranium Content to Some Trace Elements

Scatter diagrams were plotted to aid in testing the significance of the relationship of the uranium content in the 50 samples to individual trace element content. The statistical test used in this analysis was the "coefficient of medial correlation" (17). The value of this coefficient was calculated for each scatter plot and compared with values given by Quenouille for the 5 percent and 1 percent significance levels. The 1 percent level in particular indicates a high degree of correlation between the variables. Minor elements showing a correlation with uranium at the 5 percent significance level are Ba, Cu, and Ni. Correlation at the 1 percent significance level is indicated for Fe, As, Co, Mo, and Pb. Other elements tested were Sb, Sn, V, Mn, Zn, and Ag. Although it is possible that with more data the 5 percent level might be reached, especially in the case of silver, significant association of these elements with uranium is not indicated by the available data.

The analyses furnish information on the assemblage of other elements associated with uranium in the mineralizing solutions. Deposition of uranium paralleled rather closely that of iron, lead, molybdenum, arsenic, and cobalt, and less markedly, nickel, copper, and barium. This information agrees with the observed association of fine opaque sulfide and sulfo-salt minerals and uraninite described previously. The relationship of dark vein quartz color with high concentration of elements present in inclusions of opaque vein minerals, described previously, is borne out by the analyses.

SUMMARY

The "siliceous reef" uranium-bearing veins of the Boulder batholith are characterized by a gangue of quartz that occurs in small interlocking grains from about one to twenty microns across. Opaque inclusions of sulfide minerals and uraninite occur as small isolated grains, commonly less than ten microns across. The veins are of steep dip, strike east to northeast, vary in thickness from a fraction of an inch to a foot or two, and commonly have branching and anastomosing patterns along the strike.

An envelope of strongly altered granodiorite encloses all of the "siliceous reef" veins. The alteration is similar in all of the deposits and shows no differences along ore-bearing and barren portions. The essential minerals of the granodiorite, in increasing order of stability in the hydrothermal environment, are hornblende, andesine (An_{30} to An_{36}), biotite, orthoclase, and quartz. The sheet structure silicate minerals reach their maximum development, with increasing distance from the vein, in the order sericite (muscovite polytype 1M, in part), kaolinite, and montmorillonite. This sequence is the same as that found at Butte in the southern part of the batholith, and in many other localities. The destruction of primary rock minerals and de-

velopment of secondary minerals may be correlated with increases in silica and ferric iron, decreases in alumina, total iron, ferrous iron, lime, soda, and magnesia, and little change in potash, titania, phosphorus, carbon dioxide, and sulfur. Recent data showing extensive stability fields for muscovite, kaolinite and montmorillonite indicate that specific inferences of temperatures prevailing during this alteration are not justified. However, the discontinuous nature of the sericite zone adjacent to the vein suggests that the prevailing temperatures may have ranged just above and below a minimum, perhaps less than 200° C, required for formation of muscovite.

The microcrystalline quartz vein filling varies in color from light gray to black. The color is due to the pigmentation effect of the numerous small opaque inclusions and varies with their size and concentration. The bulk of the vein quartz is of light to medium gray color. Dark gray or black vein quartz of a later stage and relatively rich in sulfides and uraninite, fills fractures in the lighter colored veins.

The gangue minerals include, besides quartz, minor amounts of opal and barite. X-ray powder patterns of several opal samples showed the chief constituent to be tridymite, with lesser amounts of low and high cristobalite probable. The opaque minerals in decreasing order of abundance are pyrite, sphalerite, galena, uraninite, tetrahedrite, argentite, chalcopyrite, and covellite. Four uraninite samples revealed a unit cell dimension varying from 5.39 to 5.46 Å.

The amount of uranium in vein samples was determined by alpha scintillation counting and by fluorimetry. Good agreement was found between determinations by the two methods, consistent with the existence of radioactive equilibrium in the vein quartz as determined for two samples by the radium method. Semi-quantitative spectrographic analyses for 28 minor and trace elements were made on 83 vein samples. Tests of correlation showed a strong tendency for association of uranium with Fe, Pb, Mo, As, and Co, and a less pronounced association of uranium with Ni, Cu, and Ba. Study of the trace element distribution relative to vein color showed that the darker colors of vein quartz commonly contain a higher concentration of those elements occurring in the opaque vein minerals.

ACKNOWLEDGMENTS

The authors wish to thank colleagues in the College of Mineral Industries, The Pennsylvania State University for their aid in various techniques: Dr. Harold Lovell and Howard Grendon in spectroscopy, Joseph Comer in electron microscopy, and Herbert McKinstry in X-ray diffraction. Dr. J. C. Griffiths guided the statistical analysis of the data. Dr. F. H. Gillery aided in the interpretation of the X-ray patterns of opal. Edith Emerson performed the fluorimetric analyses for uranium. William P. Shulhof and Dr. Donald O. Emerson collaborated in related studies and contributed helpful discussion.

Mr. L. D. Jarrard, formerly of the Butte Office of the Raw Materials Division, U. S. Atomic Energy Commission, and his staff provided maps

of the mines and guidance in the field. Messrs. Buford Miles, Dewey Hinman, and the Elkhorn Mining Company, owners of the mines studied, permitted access to their properties and provided some excellent specimens.

The research was supported by Contract No. AT (30-1)-1390 with the Division of Raw Materials and Division of Research, U. S. Atomic Energy Commission.

THE PENNSYLVANIA STATE UNIVERSITY,
COLLEGE OF MINERAL INDUSTRIES,
UNIVERSITY PARK, PA.,
Feb. 27, 1959

REFERENCES

1. Becraft, G. E., 1952, Preliminary report on the Comet area, Jefferson City quadrangle, Jefferson County, Montana: U. S. Geol. Survey Trace Elements Investigations Rept. 282.
2. ——, 1953, The Comet and Gray Eagle mines and adjacent area, Jefferson County, Montana: U. S. Geol. Survey Trace Elements Memorandum Rept. 603.
3. ——, 1956, Uranium deposits of the northern part of the Boulder batholith, Montana: ECON. GEOL., v. 51, p. 362–374.
4. Billingsley, P., and Grimes, J. A., 1918, Ore deposits of the Boulder batholith of Montana: Am. Inst. Min. Met. Eng. Trans., v. 58, p. 284–368.
5. Bowen, N. L., and Tuttle, O. F., 1950, The system $NaAlSi_3O_8$-$KAlSi_3O_8$-H_2O: Jour. Geology, v. 58, p. 489–511.
6. Emerson, D. O., and Wright, H. D., 1957, Secondary uranium minerals at the W. Wilson mine in the Boulder batholith, Montana: Am. Mineralogist, v. 42, p. 222–239.
7. Frondel, C., 1945, Effect of radiation on the elasticity of quartz: Am. Mineralogist, v. 30, p. 432–446.
8. Grimaldi, F. S., May, I., and Fletcher, M. H., 1952, U. S. Geological Survey fluorimetric methods of uranium analysis: U. S. Geol. Survey Circ. 199, p. 6–7.
9. Kerr, P. F., 1955, Hydrothermal alteration and weathering: Geol. Soc. America Special Paper 62.
10. Klepper, M. R., 1950, Forty-niner, King Solomon Ridge, and west end claims near Clancy, Jefferson County, Montana: U. S. Geol. Survey Trace Elements Memorandum Rept. 31.
11. Knopf, A., 1913, Ore deposits of the Helena mining region, Montana: U. S. Geol. Survey Bull. 527.
12. ——, 1957, The Boulder bathylith of Montana: Am. Jour. Sci., v. 255, p. 81–103.
13. Kulp, J. L., Holland, H. D., and Volchok, H. L., 1952, Scintillation alpha counting of rocks and minerals: Am. Geophys. Union Trans., v. 33, p. 101–113.
14. Meschter, D. Y., 1953, The geology and mineralogy of the W. Wilson mine near Clancy, Jefferson County, Montana: U. S. Geol. Survey Trace Elements Investigations Rept. 256.
15. Nogami, H. H., and Hurley, P. M., 1948, The absorption factor in counting alpha rays from thick mineral sources: Am. Geophys. Union Trans., v. 29, p. 335–340.
16. Pardee, J. T., and Schrader, F. C., 1933, Metalliferous deposits of the greater Helena mining region, Montana: U. S. Geol. Survey Bull. 842.
17. Quenouille, M. H., 1952, Associated Measurements: Academic Press, London, p. 44–46.
18. Raman, C. V., 1953, The structure of opal: Ind. Acad. Sci. Proc., v. 38-2, no. 5, sect. A, p. 101–108.
19. Roberts, W. A., and Gude, A. J. III, 1952, Geology of the area adjacent to the Free Enterprise uranium-silver mine, Boulder district, Jefferson Co., Montana: U. S. Geol. Survey Trace Elements Memorandum Rept. 140.
20. ——, and ——, 1953, Uranium-bearing deposits west of Clancy, Jefferson County, Montana: U. S. Geol. Survey Bull. 988-F.
21. Roy, D. M., and Roy, R., 1955, Synthesis and stability of minerals in the system MgO-Al_2O_3-SiO_2-H_2O: Am. Mineralogist, v. 40, p. 147–178.
22. Roy, R., and Osborn, E. F., 1954: The system Al_2O_3-SiO_2-H_2O: Am. Mineralogist, v. 39, p. 853–885.
23. Sales, R. H., and Meyer, C., 1958: Wall rock alteration at Butte, Montana: Am. Inst. Min. Met. Eng. Trans., v. 178, p. 9–35.

24. ——, and ——, 1950, Interpretation of wall rock alteration at Butte, Montana: Colorado School of Mines Quart., v. 45, no. 1B, p. 260–273.
25. Stringham, B., 1952, Fields of formation of some common hydrothermal alteration minerals: Econ. Geol., v. 47, p. 661–664.
26. Thurlow, E. E., and Reyner, M. L., 1950, Free Enterprise uranium prospect, Jefferson County, Montana: U. S. Atomic Energy Comm. RMO-678.
27. ——, and ——, 1952, Preliminary report on uranium-bearing deposits of the northern Boulder batholith region, Jefferson Co., Montana: U. S. Atomic Energy Comm. RMO-800.
28. Tuttle, O. F., 1952, Optical studies on alkali feldspars: Am. Jour. Sci., Bowen Volume, Pt. 2., p. 553–568.
29. Weed, W. H., 1899, Granitic rocks of Butte, Montana and vicinity: Jour. Geology, v. 7, p. 737–750.
30. ——, 1912, Geology and ore deposits of the Butte district, Montana: U. S. Geol. Survey Prof. Paper 74.
31. ——, and Barrell, J., 1901, Geology and ore deposits of the Elkhorn mining district, Jefferson Co., Montana: U. S. Geol. Survey Twenty Second Ann. Rept., Pt. 2, p. 535–543.
32. Wright, H. D., 1956, Relationship of uranium-bearing vein deposits in the Boulder batholith, Montana: Abstract in XX Congreso Geologico Internacional, Resumenes de los Trabajos Presentado, p. 107–108. (In press, Congress Proceedings.)
33. ——, and Emerson, D. O., 1957, Distribution of secondary uranium minerals in the W. Wilson deposit, Boulder batholith, Montana: Econ. Geol., v. 52, p. 36–59.
34. ——, and Shulhof, W. P., 1957, Mineralogy of the Lone Eagle uranium-bearing mine in the Boulder batholith, Montana: Econ. Geol., v. 52, p. 115–131.
35. ——, Bieler, B. H., Shulhof, W. P., and Emerson, D. O., 1954, Mineralogy of uranium-bearing deposits in the Boulder batholith, Montana: U. S. Atomic Energy Comm. RME-3095.
36. Yoder, H. S., and Eugster, H. P., 1955, Synthetic and natural muscovites: Geochim. et Cosmochim. Acta, v. 8, p. 225–280.

Economic Geology
Vol. 55, 1960, pp. 383–386

REJUVENATION OF PITCHBLENDE IN HERCYNIAN ORE DEPOSITS

C. F. DAVIDSON

ABSTRACT

In a majority of instances, geochronological studies on pitchblende samples from the Hercynian granites of Western Europe reveal an age much younger than that of the granite plutons. This youthfulness is attributed to rejuvenation of an initial mineralization emplaced in Hercynian times. Before the geological history of such deposits can be correctly interpreted from mineragraphic investigations, the possibility of there having been several periods of reworking must be recognized.

Associated with the Hercynian granites of Western Europe, in southwest England, in France, Spain and Portugal, in the Vosges and the Black Forest, and in the Saxon-Bohemian Erzgebirge, there are many occurrences of pitchblende, some of them supporting important mines. As a generalization, these occurrences may be classified into four main types of deposit:

(1). Zoned tin-copper lodes, partly within the granites and partly in the metamorphic aureoles, with pitchblende occurring in the mesothermal copper zone generally where there is diabase wall rock. Examples are in the E-W lodes of Cornwall, at Wheal Trenwith, Wheal Providence, Geevor and elsewhere. These veins have given rise to important mines for tin and copper, but they are not significant sources of uranium.

(2). Mesothermal lodes with nickel-cobalt-bismuth-silver, mostly in the aureoles of the granites. Both in Cornwall and the Erzgebirge they trend N–S and postdate the E–W lodes. The N–S lodes have been important commercial sources of pitchblende, at South Terras in Cornwall and (with silver and cobalt) at Jachymov, Schneeberg, Johanngeorgenstadt, and elsewhere in Bohemia and Saxony.

(3). So-called epithermal lodes carrying sooty or massive pitchblende, generally with some pyrite and in places with galena, chalcopyrite, blende and covellite. They are found characteristically in the central zone of the Hercynian chain, occurring almost always within the granite batholiths, with a dominantly NE trend in Portugal and NW trend in France. At Urgeiriça and elsewhere in Portugal and at La Crouzille and other localities in France they have supported important uranium mines, some worked to a depth of more than 500 meters.

(4). Disseminated mineralization, perhaps formed by a hydrothermal flux from the Hercynian granites, occurring in sediments close to the plutons. In several districts of Portugal such mineralization occurs in pre-Ordovician schists. Disseminated uranium in black shales of Westphalian age downfaulted against the granites of the Vosges may be comparable.

Within the last few years a number of absolute age determinations have been executed on minerals from some of these deposits, but the scattered results have not hitherto been collected together. A compilation of these data (Table 1) provides grounds for interesting inferences on the mode of genesis of the ores.

TABLE 1

'HERCYNIAN' MINERALIZATIONS IN EUROPE

Material	Locality	Assay method	Age, m.y.	Reporter	Reference
Granite	Dartmoor, Cornwall	K/A on biotite	305	Mayne et al.	(16)
Granite	Bodmin, Cornwall	Chemical on monazite	290	Holmes	(10)
Granite	Andlau, Vosges	Pb/α on zircon	240	Hée et al.	(9)
Granite	Natzwiller, Vosges	Pb/α on zircon	300	Hée et al.	(9)
Granite	Lausitz, Saxony	Pb/α on zircon	280–315	Schurmann et al.	(21)
Granites	Black Forest (7 groups)	K/A on whole rocks	275–306	Gentner and Kley	(8)
Pegmatite	Sierra de Albarraña, Spain	Chemical on uraninite	340	Lopez de Azcona	(15)
Pegmatite	Sierra de Albarraña, Spain	Isotopic on uraninite	250, 325, 280	Lopez de Azcona	(15)
Pegmatite	Sierra de Albarraña, Spain	Rb/Sr on muscovite	280	Lopez de Azcona	(15)
Pitchblende	Jachymov, Bohemia	207/206	337 $\pm$ 61	Avdzeiko	(1)
Pitchblende	Geevor, Cornwall	Full isotopic	307, 288, 288, 300	Darnley	(3)
Pitchblende	Jachymov, Bohemia	206/238, 207/206	220, 145	Nier	(17)
Pitchblende	Jachymov, Bohemia	Pb^{210}	206	Kulp	(13)
Pitchblende	Schmiedeberg, Sudeten	207/206	210 $\pm$ 50	Ehrenberg	(6)
Pitchblende	Wittichen, Black Forest	"Isotopic"	235	Leibiger	(12)
Pitchblende	Wölsendorf, Bavaria	Chemical	200	Hecht and Kroupa	(23)
Pitchblende	"Central Europe"	207/206	108 $\pm$ 57	Avdzeiko	(1)
Pitchblende	Wittichen, Black Forest	206/238, 207/235	111, 97	Kulp	(12)
Pitchblende	La Crouzille, France	Full isotopic	146, 147, 157	Demay	(5)
Pitchblende	Urgeiriça, Portugal	Full isotopic	86, 81, 126	Stieff	(22)
Pitchblende	Lenteiros, Portugal	Full isotopic	97, 97, 118	Stieff	(22)
Pitchblende	Lenteiros, Portugal	Full isotopic	86, 89, 90	Stieff	(22)
Pitchblende	Lenteiros, Portugal	Full isotopic	71, 79, 79	Horne	(11)

Although the Hercynian granites probably vary somewhat in age, it would seem that most of them date around 280–310 m.y., values which are in keeping with their stratigraphical position if one assumes a short extension of the Holmes B time scale (4). The dated uraninite-bearing pegmatites of Sierra de Albarraña are essentially coeval with this main phase of granite formation; there is excellent agreement with a full isotopic assay of pitchblende from the Geevor tin lode recently reported by Darnley (3); and there is a Russian isotopic assay of lead from Jachymov pitchblende reported by Avdzeiko (1) which, according to the writer's calculations, gives about the same age. The possible error quoted in this last determination arises from uncertainties about the decay constants. When, however, we look at the main group of determinations on the pitchblendes of the polymetallic silver veins, and of the fluorite veins of Wölsendorf, it is seen that these appear to post-date the associated granites by about 100 m.y. An important question which thus arises in whether these seemingly late-Permian lodes are really so much younger than the granites, or whether this apparent relationship derives solely from the re-working of pitchblende within fissures that were originally penecontemporaneous with the intrusions. The contemporary date of the Cornish pitchblende from an E–W vein, and the presence within the N–S Jachymov ore-bodies of a pitchblende coeval with the granites, together suggest strongly that a rejuvenation has occurred in late Permian or early Triassic times. An isotopic examination of the galena-lead in the veins should be of interest in this connexion, for an abnormally high radiogenic component would indicate regeneration.

That a local rejuvenation of the Hercynian pitchblende at Jachymov took place during Tertiary times was demonstrated many years ago by de Launay (14), who found veinlets of pitchblende cutting Tertiary phonolite dikes. It was assumed that a small-scale hydrothermal re-working was induced by the later volcanism. Perhaps this explanation may be applied to the two ages at Wittichen (where, however, the wall-rock is granite). But to account in this way for the apparent Upper Mesozoic age of the mineralization in France and Portugal is quite another matter. In these countries there are many pitchblende lodes supporting the largest uranium mines in Europe, descriptions of which have recently been given by Sarcia (20), Roubault (19), Pires Lobato (18) and others. The lodes are characteristically situated within the Hercynian granites, and are made up mostly of brecciated fault rock and banded quartz, with much red jasper and chalcedony. In Portugal they consistently exhibit a NE trend parallel to the tectonic lines imposed upon the Iberian peninsula in Tertiary times, and it is widely maintained by geologists in that country that the mineralization was derived from the Hercynian granites by lateral secretion or some such process during the Alpine orogeny. In France, where the lodes trend NW, an age of *Hercynien tardif* is usually accepted, long post-dating the tin-wolfram mineralization. Many instances are known where the distribution of ore is controlled by late Hercynian (Stephanian) lamprophyre, microgranite and jasperized dolerite dikes; and generally the uranium enrichment is accompanied by extensive kaolinization, sericitization, and chloritization of the granite, locally also by much albitization. Much of the mineralization of marginal or sub-marginal grade takes the form of big dike-like stockworks; and a comparable slight enrichment in uranium is found in the granitic walls of many veins.

To explain why Hercynian granites should give rise to a widespread mineralization of near-Tertiary age is far from easy. The hypothesis that the uranium has been derived from the rocks of the batholiths by lateral secretion in mid-Cretaceous times, after the intrusions had been unroofed, is not well supported by chemical evidence, and this view is contradicted by the circumstance that whereas in the granites the content of thorium exceeds that of uranium, there is virtually no thorium in the pitchblende veins. In any secretion process that can be envisaged one would expect the two elements, derived from the same primary minerals, to behave sympathetically. Perhaps the most likely explanation of the anomaly is that the uraninite mineralization (with associated sulfides) was emplaced in hydrothermal cross-course lodes during Hercynian times, late in the history of the intrusions; and that in the early Alpine earth-movements these zones of weakness were re-opened and revivified, permitting the movement of solutions in which the pitchblende was rejuvenated. On such a hypothesis the geological history of the French and Iberian deposits (the similarity between which has been emphasized by Geffroy and Sarcia (7) does not differ materially from that advanced for the lodes of Central Europe. It would thus not be surprising if some older pitchblende were discovered in some future mass-spectrographic studies of Portuguese ores.

The pattern of mineralization in these Hercynian lodes recalls the pattern found in the work of Collins and others (2) on the pitchblende veins of Athabaska, where the apparent age of ore deposition has been found to vary widely within the limits 850 to 1,850 m.y. Evidently rejuvenation of hydrothermal veins by reworking of the mineralization is a commoner phenomenon in ore deposits than is generally realized.

UNIVERSITY OF ST. ANDREWS,
SCOTLAND.
September 28, 1959

Note added in proof (2nd November 1959): Since this paper was written, Dr. Henry Faul of U. S. Geological Survey has kindly informed the writer of potassium: argon age determinations which he has undertaken on the biotite of the Dartmoor granite, these giving values of 292 and 288 m.y., in reasonable agreement with Dr. Mayne's value of 305 m.y. quoted above.

REFERENCES

1. Avdzeiko, G. V., 1958, Rol' isotopnogo analiza svintza v opredelenii geologicheskogo vozrasta: *Trudy Radievogo Instituta*, Leningrad, v. 8, p. 198.
2. Collins, C. B., et al., 1952, Age determinations for some uranium deposits in the Canadian shield: Proc. Geol. Ass. Canada, v. 4, p. 15.
3. Darnley, A. G., 1959, Uraninite from Geevor, Cornwall: Geol. Surv. Gt. Britain Age Determination Report, no. 6.
4. Davidson, C. F., 1959, How old is the Cambrian System?: Nature, v. 183, p. 768.
5. Demay, A., 1953, Détermination de l'âge absolu d'une pechblende: C. R. Ac. Sc., v. 237, p. 48.
6. Ehrenberg, H. F., 1953, Isotopenanalysen an Blei aus Mineralien: Z. Physik, v. 134, p. 317.
7. Geffroy, J., and Sarcia, J. A., 1959, Le notion de 'gite epithermal uranifère': Bull. Soc. Géol. France, ser. 6, v. 8, p. 173.
8. Gentner, W., and Kley, W., 1958, Argonbestimmungen an Kaliummineralien V: Geochim. Cosmochim. Acta, v. 14, p. 98.
9. Hée, A., et al., 1957, Détermination de l'âge de deux granites de la chaine des Vosges: Annales Géophysiques, v. 18, p. 135.
10. Holmes, A., 1948, Monazite from Bodmin Moor, Cornwall: Proc. Roy. Soc. Edin., B, v. 63, p. 115.
11. Horne, J. E. T., 1956, Age of pitchblende from Lenteiros, Reboliero, Portugal: Geol. Surv. Gt. Britain Age Determination Report, No. 1.
12. Kirchheimer, F., 1957, Bericht über das Vorkommen von Uran in Baden-Württemberg: Abh. geol. Landesamt Baden-Württemberg, no. 2, p. 90.
13. Kulp, J. L., Broecker, W. S., and Eckelmann, W. R., 1953, Age determination by the lead 210 method: Nucleonics, v. 11, p. 19.
14. de Launay, L., 1913, Traité de Métallogénie: Paris (Beranger), v. 2.
15. Lopez de Azcona, J. M., La edad de los uraninitas de la Sierra Albarraña: Inst. geol. min. España notas y comunicaciones, no. 45, p. 3.
16. Mayne, K. I., Lambert, R., and York, D., 1959, The geological time-scale: Nature, v. 183, p. 212.
17. Nier, A. O., 1939, The isotopic composition of radiogenic lead: Phys. Rev., v. 55, p. 153.
18. Pires Lobato, C., 1958, Tectonic synthesis of Portuguese uranium deposits: Proc. Second Conf. Peaceful Uses of Atomic Energy, v. 6, p. 632.
19. Roubault, M., 1958, Géologie de l'Uranium: Paris (Masson).
20. Sarcia, J. A., et al., 1958, Geology of uranium vein deposits of France: Proc. Second Conf. Peaceful Uses of Atomic Energy, v. 6, p. 592.
21. Schurmann, H. M. E., et al., 1956, Age determinations of magmatic rocks: Geologie en Mijnbouw, v. 18, p. 312.
22. Stieff, L. R., 1958, Geochronology: Geological investigations of radioactive deposits: U.S.G.S. Report TEI-740, p. 300.
23. Ziehr, H., 1955, Das wölsendorfer Flusspatrevier: Erzmetall, v. 8, no. 9.

Economic Geology
Vol. 55, 1960, pp. 387-398

CHALCOPYRITE BLEBS IN SPHALERITE AT JOHNSON CAMP, ARIZONA

ARTHUR BAKER III

ABSTRACT

Pyrometasomatic sphalerite-chalcopyrite deposits at Johnson Camp are pipes as much as 2,000 feet long, formed along bedding-plane channelways of mineralizing solutions rather than at the intersections of cross-cutting channels with favorable beds. Nearly all of the sphalerite contains numerous microscopic blebs of chalcopyrite. The principal control for variations in the abundance and size of these blebs is stratigraphic, and an attempt to use bleb patterns as a guide to new ore failed because of this stratigraphic control. Blebs are not present in ore that contains bornite. The blebs originated by exsolution as the ore deposits cooled, but before the mineralizing solutions stopped circulating.

INTRODUCTION

Microscopic study of specimens from the Republic Mine in the Johnson Camp District, Cochise County, Arizona disclosed the presence of numerous minute blebs of chalcopyrite disseminated in the sphalerite that is the most abundant sulfide. The specimens studied, although from random locations and few in number, showed a pattern of distribution that seemed related to the positions of the specimens within the orebodies: larger and more numerous blebs in deep parts of the orebodies, and smaller and fewer blebs in the shallower parts (1, p. 1277). On the chance that such a pattern, if confirmed, would serve as a guide in the search for extensions of orebodies, the Coronado Copper and Zinc Co., major operator in the district, relieved the writer of many of his other duties as mine geologist to pursue more detailed research into this possibility. The Moore Mine was chosen for the project because of the better opportunities it offered for collecting specimens.

The writer is greatly indebted, not only to the management of the Coronado Copper and Zinc Co. in general, but in particular to Mr. Fred E. Gray, Manager of the Johnson Camp Unit, and to the late Mr. Roy W. Moore, President of the Company, for encouragement during the study and permission to publish the results. He wishes also to acknowledge with thanks the comments and criticisms of John R. Cooper, Oscar W. Jarrell and Charles F. Park Jr.

JOHNSON CAMP GENERAL GEOLOGY

Johnson Camp has produced about 1,000,000 tons of ore with a value of about $20,000,000. The ore deposits are zinc-copper, pyrometasomatic replacement deposits in Paleozoic limestones, principally in the Cambrian Abrigo formation. Except for a single lamprophyre dike, there are no igneous rocks

known within the mineralized area, but a quartz monzonite stock half a mile west of the district is considered part of the source of the mineralizing fluids. The sediments form a homocline striking northwest and dipping about 40° northeast; superimposed on this homocline are irregularly-spaced, shallow rolls that are important in localizing some of the orebodies. Other orebodies are localized by the intersections of faults with the favorable beds, but most faults are barren.

Orebodies are found almost exclusively in a single fifty-foot thickness of originally sandy and shaly limestone beds, altered before the introduction of ore to garnetite and hornfels, at the top of the middle member of the Abrigo formation. The orebodies are tabular to pipe-like masses with their two longest dimensions in the plane of the bedding, associated with similarly-shaped but larger bodies of garnetite in the same and the immediately underlying beds. The overlying upper Abrigo, originally impure dolomite, is altered uniformly to orthoclase-diopside tactite throughout the district. Two major clusters of orebodies are known in the district, one opened in the Republic Mine (1, Fig. 4) and the other in the Moore Mine. In each of these clusters nearly all of the orebodies, though differentiated for mining purposes, actually form a single continuous body except for fault offsets. This continuity of ore pipes along the favorable beds suggests that the pipes represent channels along which the mineralizing solutions flowed, rather than the intersections of cross-cutting channels with the favorable beds, and that therefore minor changes in the paragenesis, such as the original study indicated, could be expected along the length of these channelways and ore pipes.

The only valuable ore minerals at Johnson Camp are sphalerite and chalcopyrite; the ore averages about 6 percent Zn and 2 percent Cu. Pyrite is ubiquitous but seldom abundant. In parts of some orebodies bornite is found, but not in quantities to contain more than one-fourth of the total copper present; traces of bismuth minerals (discovered by Kanji Shiobara, personal communication) are commonly associated with bornite. Rare grains of magnetite and scheelite are found everywhere in the ore. The principal gangue minerals are grossularite, diopside and quartz, remnants of the earlier-formed garnetite host rock, and unreplaced bands of hornfelsed shale. Chalcopyrite and sphalerite have been observed veining all other minerals except bornite and bismuth minerals, with which they have mutual boundaries, so they are the youngest of the major minerals.

The ore is strongly banded, the sulfides being concentrated in bands a few inches wide separated by bands of nearly barren garnetite; the overall grade of the ore depends on the thickness and spacing of the sulfide bands. Within the sulfide bands much of the chalcopyrite occurs as nearly pure bands and lenses, but the sphalerite is almost invariably intergrown with at least a small percentage of chalcopyrite. In the intergrown areas, grain sizes are seldom greater than 5 mm in diameter. Contacts between the two minerals are always of the mutual boundary type, and it is impossible to assign any sequence of formation to them. Rare instances of microscopic veinlets of chalcopyrite traversing sphalerite and of sphalerite traversing chalcopyrite have been observed, demonstrating that each mineral was locally later than the other. These occurrences are so rare and unlike the normal relations that

they can have no significance as to the relative ages of the bulk of the chalcopyrite and sphalerite.

More detailed information on the geology, ore occurrences and metamorphism is given in the papers by Baker and Cooper (1, 3, 4).

CHARACTERISTICS OF BLEBS

In a study of the relations of sphalerite to other sulfides, Teas (8) found chalcopyrite blebs in sphalerite of ores of all types from pyrometasomatic to epithermal, but not in "meteoric deposits" (Joplin, Mo., Southwest Wisconsin, etc.). He noted numerous blebs in pyrometasomatic and intermediate-vein zone deposits, fairly numerous blebs in deep-vein zone deposits, and small and few blebs in shallow-vein zone deposits (8, Table 2, p. 77). Many other writers make brief mention of the presence of chalcopyrite blebs in sphalerite in individual districts, but none give any details on their distribution. Teas also noted (8, p. 71) that the presence of pyrrhotite seemed to be unfavorable for the development of blebs. In the present study is was found that the presence of bornite was unfavorable.

The blebs are ordinarily subangular, equidimensional to oblong in cross section, ranging in size from the minimum discernable under the microscope to 0.1 mm in diameter. Commonly they are aligned along crystal directions of the sphalerite, and in such cases they may coalesce to form knobby stringers or, in extreme cases, fairly smoothwalled stringers. Bleb chalcopyrite in the Johnson Camp ores makes up a maximum of 8 percent of the volume of the sphalerite.

The distribution of blebs within individual sphalerite grains follows a single general pattern with minor variations. In most instances, three zones can be distinguished: a barren rim, a zone of abundant blebs increasing in size inward, and a central core. The barren rim, in which no blebs at all occur, is about 0.03 mm wide, in all cases present along contacts with chalcopyrite masses, commonly present along contacts with other sphalerite grains and in places present along contacts with gangue minerals. The zone of abundant blebs begins with blebs of barely-distinguishable size at the inner edge of the barren rim, and through a width of about 0.1 mm the blebs increase to the maximum size found in the grain. In most cases the core is occupied by large blebs of uniform size, in places with distinctly smaller-sized blebs occupying the intervening spaces, but in other places the increase in bleb size continues to the center of the grain, which is occupied by a few relatively tremendous blebs. In a few specimens at Johnson Camp the cores of sphalerite grains are barren, containing no blebs at all; judging by the literature, barren cores are the rule in some districts. The maximum and modal bleb sizes and the pattern of distribution are about the same in all the sphalerite grains in any given specimen.

METHOD OF STUDY

Since the stratigraphic control of ore is so rigid on a major scale, it was suspected that stratigraphy might also have some influence on the small scale of the bleb patterns, so two separate suites of specimens were collected. One

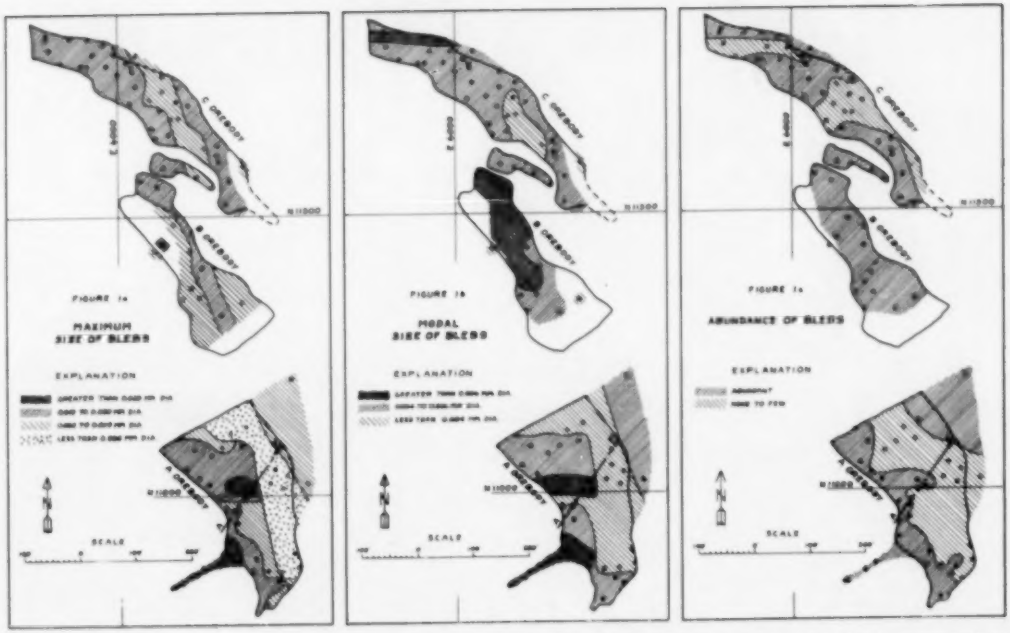


FIG. 1. Moore Mine orebodies in horizontal projection, showing distribution of bleb characteristics. Open circles represent locations of samples with blebs in sphalerite, filled circles represent locations of samples with no blebs. Stope areas outlined by heavy lines; samples from outside these lines are from sulfide bands too thin to be mined.

suite was intended for study of areal distribution of bleb patterns, and was collected from various parts of the Moore orebodies and surrounding mineralization, but in every case from as close as possible to the hanging wall. Since the hanging wall varies by as much as twenty feet stratigraphically, this meant a twenty foot range in the stratigraphic location of the specimens. The locations of the specimens for this study are shown in horizontal projection in Figures 1a, 1b and 1c. The second suite was intended for study of possible stratigraphic or cross sectional variations in patterns, and was collected along a well-exposed cross section through the Moore "A" Orebody; the location of the section is shown on the horizontal projections and the locations of the specimens on the section are shown in Figures 2a, 2b, 2c and 2d. One hundred twenty-one specimens were included in the areal study (24 specimens from outlying mineralization are not shown on Figure 1) and 63 specimens in the cross-sectional study. An additional 39 specimens that did not belong to either of these groups, and half a dozen thin sections from various locations, were also studied.

To provide as much objectivity as possible in what was inherently a highly subjective study, the specimens were assigned random numbers and the polished sections were studied without knowledge of their locations. Dimensions were measured with a grid eyepiece, so maximum bleb sizes given are accurate. Modal bleb sizes, however, were determined by choosing a few blebs that were estimated to be representative of the modal size and measuring these, so there was room for error in estimating this feature. Abundances also were estimated, not measured. As a check, about 20 percent of the polished specimens were fed back into the circuit and restudied; in most instances the estimates and measurements on both runs were similar enough so that they fell into the same classification.

For each specimen the following data were noted: (1) maximum bleb size; (2) modal bleb size; (3) relative abundance of blebs; (4) grain sizes of sphalerite, relative proportions of sphalerite and chalcopyrite, and boundary relations between the two minerals; (5) any other items of interest, such as presence of barren cores, presence of other sulfides, the rare cases of late sulfide veinlets, etc. For some specimens blebs were counted and measured for an estimate of the total volume of chalcopyrite present in the sphalerite.

RESULTS OF THE STUDY

The results of the areal study are summarized in Figures 1a, 1b and 1c. There is a moderately strong correlation between bleb size and abundance of blebs, but there is no overall pattern ascribable to variations caused by position along the mineralizing solution channel. In fact, the variations that do appear correlate quite closely with changes in the stratigraphic position of the hanging wall: areas that have the same bed at the hanging wall have similar bleb sizes and abundances, and areas with the hanging wall a few feet higher or lower have different sizes and abundances.

Figures 2a, 2b and 2c, summarizing the results of the cross sectional study, indicate the reason for the variations found in the areal study: the size and abundance of blebs is strongly influenced by stratigraphy. The least subjective feature, maximum bleb size, shows the stratigraphic control most

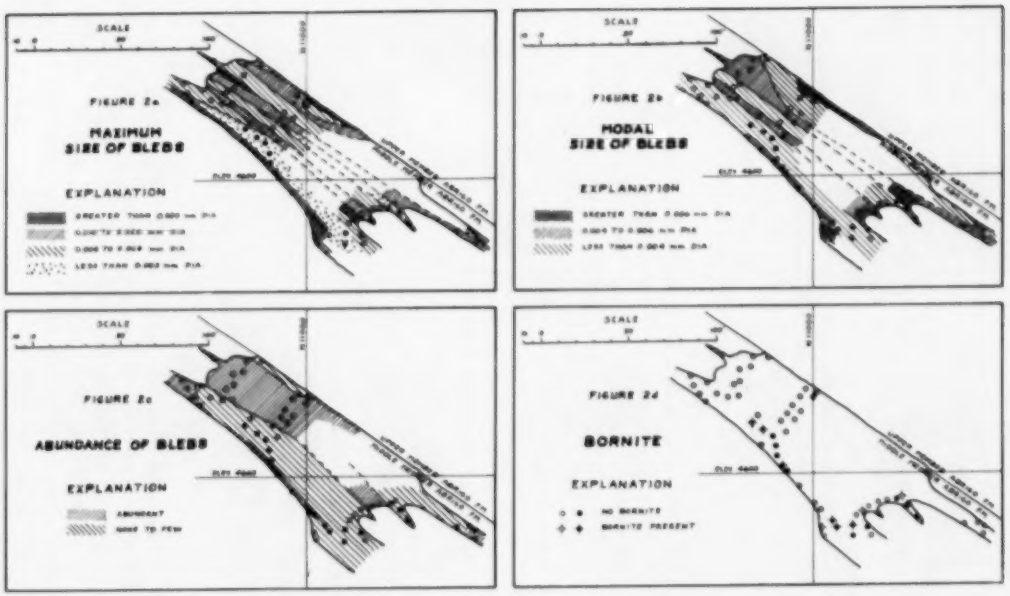


FIG. 2. Cross section A-A′ through A Orebody, looking northwest. Open circles represent locations of samples with blebs in sphalerite, filled circles represent locations of samples with no blebs. Ore-body is outlined by heavy lines.

strongly, beds less than 10 feet thick having blebs of the same size range all across the section. The stratigraphic control is less distinct but still clear in the distribution of the more subjective features, modal bleb size and abundance of blebs. Thus, the project was a failure so far as its economic purposes were concerned; it is still possible that by restricting one's sampling to a single bed, preferably no more than a couple of feet thick, significant variations in bleb distribution might be found, but at Johnson Camp alteration is too intense to permit following such a restricted bed over any useful distance. A similar study in an orebody in a homogeneous host rock might be more successful.

Figure 2d demonstrates the relations between bornite and blebs: all of the specimens in which no blebs were found lie in a part of the orebody in which bornite is found, and most of them lie in specific beds containing bornite whether or not it occurs in the same specimen. Although it could not be shown on the cross section, even those bornite-containing specimens that do have blebs have very very few, almost none.

A particular search was made during the work for evidence that would throw light on the age and origin of the blebs; in particular, veinlets of hypogene minerals traversing sphalerite were hoped for. Half a dozen such veinlets, all of chalcopyrite, were found, but in most of them the relations to the blebs were obscure. In view of the possibility of supergene chalcopyrite, it should be mentioned that the Moore orebodies are blind orebodies 400 to 600 feet below the surface; the ore shows no sign of oxidation except in a few strong shears, where it is completely oxidized.

Photomicrographs of the two most informative veinlet occurrences are shown in Figures 3a, 3b and 3c. The blebs are zoned around the larger veinlet in Figures 3a and 3b just as they are zoned around other chalcopyrite masses, so this vein must be either older than or contemporaneous with the blebs. The enlarged ends of the vein segments suggest that the veinlet was formed by draining exsolved chalcopyrite from the surrounding sphalerite—the continuous part of the vein could drain only the sphalerite to the sides, but the ends drained the sphalerite ahead of them as well, thus acquiring more chalcopyrite. The sphalerite in this specimen contains not only the large blebs, but also a multitude of tiny blebs barely visible in the photomicrograph that are found all through the sphalerite but are particularly numerous close to the veinlet.

Parallel to the larger veinlet is a much smaller one that cuts through at least the larger-sized blebs, indicating a younger age for this veinlet. Figure 3c shows a group of veinlets of distinctly younger age than the blebs they traverse. The matching walls of these latter veinlets indicate that they are fissure fillings rather than replacements.

The zoning of the blebs with respect to the larger veinlet of Figure 3a demonstrates that the blebs are younger than the host sphalerite, since the sphalerite must have been present before the veinlet was formed, and the veinlet before the blebs. Thus, the blebs cannot be unreplaced remnants of pre-existing chalcopyrite. The cross-cutting relations of the other veinlets, however, demonstrate that the blebs are older than at least the latest chalcopyrite deposition.

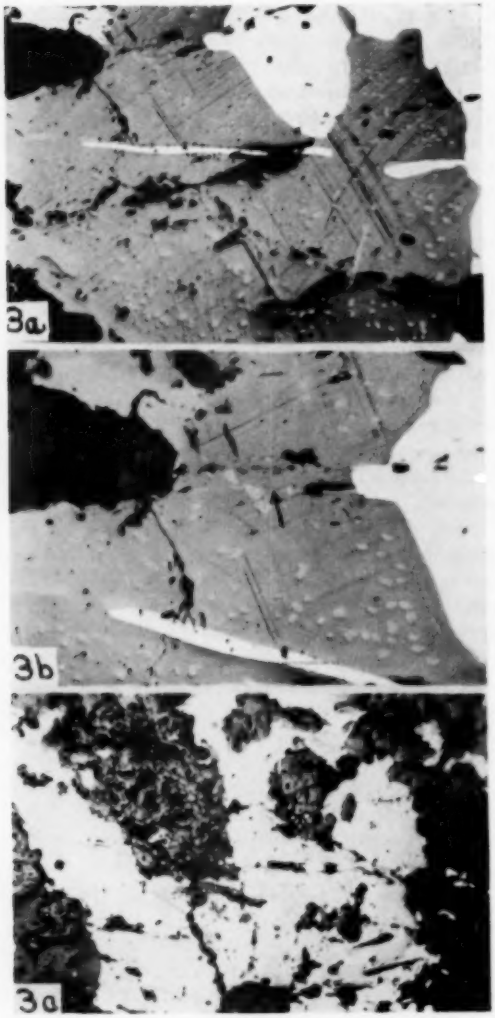


FIG. 3.

3a. Exsolution veinlet of chalcopyrite with characteristic rim pattern in surrounding blebs. × 35. 3b. Upper left half of 1a. Note small post-bleb chalcopyrite veinlet above exsolution veinlet (arrow), and numerous barely-visible blebs in vicinity of exsolution veinlet. × 70. 3c. Post-bleb chalcopyrite veinlets. × 35. Gray is sphalerite, white is chalcopyrite.

The limited thin section work disclosed a persistent color zoning in the sphalerite. Around the edge of each grain the sphalerite has a prominent purplish coloration, but the center of each grain is clear and honey-colored. The purple zone contains all of the rim barren of blebs, and fades out inward into the zone of increasing bleb size, while the clear center is approximately coextensive with the core of uniform bleb size. The gradational contact between the color zones is more irregular than the contact between bleb zones, and the purple color penetrates farther along what seem to be obscure fractures though not along the more obvious ones.

SIGNIFICANCE OF BLEBS

Despite the common occurrence of chalcopyrite blebs in sphalerite, most published studies of sulfide paragenesis pass over them with brief mention. Apparently the general belief is that they are of exsolution origin, a belief supported by the only published experimental work done on this particular pair of minerals. Buerger (*2*) demonstrated that heating of natural chalcopyrite-sphalerite intergrowths to temperatures above 350° C produced changes in color of the sphalerite that could best be explained by its having taken into solution chalcopyrite from the adjoining masses. After one run he found minute new chalcopyrite blebs surrounding older pre-existing blebs, indicating that chalcopyrite had been dissolved from the larger blebs and exsolved to form new blebs during the cooling of the specimen. The cooling process was accomplished by an air blast, and took only a few minutes (*2*, pp. 525–530).

One of the notable features indicated by Buerger's work and by other investigators' work on different pairs of minerals is the rapidity with which exsolution is carried to completion—bornite and chalcopyrite, for example, unmix to form bleb patterns similar to the sphalerite-chalcopyrite patterns, and others, within a 24 hour cooling period (*7*, Fig. 6). The basic requirement for solid solution of minerals, and subsequent exsolution, is a quite close similarity between the crystal structures of the two minerals, which the chalcopyrite-sphalerite pair has, and similarity of the atomic diameters of the ions involved, which copper and zinc have (*5*, p. 99).

The only other hypothesis, besides exsolution, that has come to the writer's attention to explain the origin of blebs is that blebs in sphalerite from Magdalena, New Mexico were formed by late, copper-rich, iron-poor solutions that seeped into sphalerite and acquired from it enough iron to form chalcopyrite, which then precipitated to form the blebs (*6*, p. 95). Aside from Buerger's experimental evidence for an exsolution origin for the chalcopyrite blebs, a strong argument against this latter hypothesis is the requirement of copper-rich, iron-poor solutions introduced into nearly all sphalerite-bearing deposits at about the same late stage in their formation. This is no problem for the exsolution theory, since (for hydrothermalists, at least) all ore deposits must pass from a high temperature to a low temperature, and somewhere in this transit must pass through a stage in which the temperature is right for exsolution to take place. The absence of blebs from telethermal deposits (Teas' meteoric deposits) probably signifies that they were formed

at temperatures below which chalcopyrite could dissolve in sphalerite, and might be used as a criterion to distinguish such deposits, as Teas (8, p. 82) pointed out.

The Johnson Camp evidence supports the theory of exsolution origin of the blebs. Since an excellent discussion of the theory already exists (5, p. 81–114, esp. p. 98–102), no general consideration of it is needed here. However, the present study indicates some specific points that are worthy of mention.

One of these points is the distribution of blebs, both within the orebody in general and within specific sphalerite grains as well. The differences in the amount of bleb chalcopyrite (as shown by the bleb abundance and size) in different beds is probably attributable to differences in the amount of chalcopyrite available at the time of sphalerite formation. Unfortunately no assay information is available for the sampled cross section, but it was noted that in general the sphalerite with few blebs was found in specimens in which there was little chalcopyrite, while specimens with much chalcopyrite had abundant blebs. Since the proportion of chalcopyrite to sphalerite varies considerably from bed to bed, with some beds containing much of one and almost none of the other, this probably accounts for the stratigraphic control of bleb abundance and size. Published accounts indicate that in districts where chalcopyrite is abundant, blebs are abundant also, and vice versa, as for example at Magdalena, New Mexico, where both are rare (6, p. 95). It follows from this reasoning that the raw materials for chalcopyrite were present when the sphalerite was being formed, to be dissolved in it, and therefore that the non-bleb chalcopyrite present was probably deposited either before sphalerite or simultaneously with it.

Edwards explains the zonal distribution of the blebs within individual sphalerite grains as the result of progressive exsolution—initial exsolution into partial solid solutions, which segregate by solid diffusion and then continue to exsolve further with continued cooling—and concludes that the barren rims result from "draining" of exsolved chalcopyrite to adjacent non-bleb masses of chalcopyrite (5, p. 99 and 88). Certainly, it is difficult to explain such rare occurrences as the larger veinlet illustrated in Figures 3a and 3b by any greatly different mechanism. The less common presence of barren rims along contacts with minerals other than chalcopyrite shows that the draining is not a matter of adjacent chalcopyrite "drawing" out the exsolved chalcopyrite, but rather one of the sphalerite itself "forcing" it out. In at least some cases the forced-out chalcopyrite does not redeposit at the edges of the sphalerite grains, but migrates elsewhere. Good illustrations of this are Lasky and Loughlin's Plates 27B and 27D (5), which show several sphalerite grains with barren rims but no non-bleb chalcopyrite at all in the field. The removal of the exsolved chalcopyrite in such cases leaves a void that must be filled with components drawn from whatever mineralizing solutions are still circulating. In some cases this will be sphalerite, and indistinguishable from the older sphalerite, but in other cases, where new sphalerite components are not available, other minerals must do. For this, the sphalerite grain shrinks and a border of other mineral is formed; Lasky and

Loughlin's Plate 27B shows such grains with borders of "either smithsonite or siderite." Since bleb formation happens rapidly, according to the laboratory evidence, and chalcopyrite once incorporated into a bleb has but little tendency to migrate out of the sphalerite grain (as witness the fact that the blebs are still present despite long slow cooling) the forcing out of exsolved chalcopyrite must be restricted to the borders of the sphalerite grains. In the interior, chalcopyrite is forced only into scattered areas—the blebs. Some of the zoning of the blebs, particularly the barren cores, may be a result of a deficiency of copper at the time the barren areas were originally formed.

The purplish coloration of the rims seen in thin sections may be caused by very numerous submicroscopic chalcopyrite blebs formed by the exsolution of material that was in transit toward the grain boundaries when the temperature finally fell too low to permit it to remain in solution. Since this material was in the process of migrating when the fatal moment arrived, it did not have time to collect into visible blebs, but instead formed a multitude of blebs each consisting of perhaps only a few molecules of chalcopyrite. The absence of color from the center of the grains indicates that here all of the exsolved chalcopyrite reached a bleb before migration was stopped. The ubiquity of the color pattern suggests that forcing out of chalcopyrite was a two-stage operation, the first stage consisting of collecting the material into blebs, with some simultaneous forcing out, and the second stage consisting of removal of chalcopyrite from the blebs and shunting it to the edges of the grain. This mechanism accounts for the characteristic bleb pattern: the rims are barren because blebs at first formed in them were completely redissolved and their materials forced out; the zone of increasing bleb size is the zone in which the redissolving process was arrested before completion; and the typical core of uniform-sized blebs is the area in which redissolution has not been active.

The presence of post-bleb chalcopyrite veinlets demonstrates that the exsolution took place while mineralizing solutions were still active, though perhaps weakly, and thus provides a geologic thermometer to estimate the temperature near but before the end of mineralization. Buerger's work (2, p. 530) indicates a temperature of 350° C to 400° C for the late mineralization, but this is subject to variations caused by field conditions. The presence in some specimens of barely-visible minute blebs (whose distribution is not related to the normal pattern), similar to those produced by Buerger by reheating chalcopyrite-sphalerite intergrowths, suggests that the Johnson Camp ores were locally subjected to late temporary increases in temperature, perhaps related to the introduction of the post-bleb chalcopyrite. These second generation blebs are present in the sphalerite illustrated in Figures 3a and 3b, which also contains a post-bleb chalcopyrite veinlet.

CONCLUSIONS

(1) Variations in bleb patterns cannot be used as a guide to ore, at least in bedded deposits, because stratigraphic variations overshadow any along-channel variations that might be present.

(2) The blebs result from exsolution of chalcopyrite-sphalerite solid solutions, as other investigators have also concluded.

(3) The abundance of bleb chalcopyrite is roughly proportional to the amount of chalcopyrite in the immediate area or bed, which perhaps means that non-bleb chalcopyrite was deposited either before or simultaneously with sphalerite.

(4) Most of the characteristic pattern assumed by the blebs within individual sphalerite grains results from the tendency of the sphalerite to force out exsolved chalcopyrite near the edges of grains, and within the grains to force it into numerous small areas—the blebs. The sphalerite grains contract enough to fill the voids left by forced-out chalcopyrite; if the chalcopyrite redeposits at the edge of the grain, that is the end of the matter, but if the chalcopyrite moves elsewhere, new material from the mineralizing solutions fills the shrinkage cracks. Barren cores do not originate by this mechanism, but simply from lack of copper at the time the barren areas of sphalerite were formed.

(5) Much of the forcing out of chalcopyrite takes place by resolution of chalcopyrite from blebs near grain boundaries, and this resolution produces the characteristic bleb pattern. Material in transit when solid solution finally becomes impossible is probably exsolved into submicroscopic blebs to produce the characteristic purplish color of sphalerite rims seen in thin sections.

(6) Exsolution takes place late in the period of mineralization but while mineralizing solutions are still circulating, so the blebs can be used as a geologic thermometer to establish the temperature of late stages of mineralization. Published experimental data indicate a temperature of 350° C to 400° C. Temporary local late increases in temperature are recorded by a second generation of very tiny blebs.

GUNNISON, COLORADO,
May 11, 1959

REFERENCES

1. Baker, A., III, 1953, Localization of pyrometasomatic ore deposits at Johnson Camp, Arizona: Am. Inst. Min. Met. Trans., v. 196, p. 1272–1277.
2. Buerger, N. W., 1934, The unmixing of chalcopyrite from sphalerite: Am. Mineralogist, v. 19, p. 525–530.
3. Cooper, J. R., 1950, Johnson Camp Area, Cochise County, Arizona: Arizona Zinc and Lead Deposits, P. 1, Arizona Bur. Mines Bull. 156.
4. ——, 1957, Metamorphism and volume losses in carbonate rocks near Johnson Camp, Cochise County, Arizona: Geol. Soc. America Bull., v. 68, p. 577–610.
5. Edwards, A. B., 1954, Textures of the ore minerals: Australasian Inst. of Mining and Metallurgy, Melbourne.
6. Lasky, S. G., and Loughlin, G. F., 1942, Minerals of the Magdalena District: Geology and ore deposits of the Magdalena Mining District, New Mexico, U. S. Geol. Survey Prof. Paper 200.
7. Schwartz, G. M., 1931, Textures due to unmixing of solid solutions: ECON. GEOL., v. 26, p. 739–763.
8. Teas, L. P., 1918, The relation of sphalerite to other sulphides in ores: Am. Inst. Min. Met. Trans., v. 59, p. 68–82.

Economic Geology
Vol. 55, 1960, pp. 399–401

SCIENTIFIC COMMUNICATIONS

COMMERCIAL CHRYSOTILE DEPOSITS, BAIE VERTE, NOTRE DAME BAY DISTRICT, NEWFOUNDLAND—PRELIMINARY NOTES

W. JAMES BICHAN

The Baie Verte bodies occupy a tabular zone of fiber development, having an almost horizontal disposition, and in one diagnostic section exhibiting a pronounced plunge of 35° to the north-northeast. The fiber-bearing deposits are discontinuous portions of those parts of the ultrabasic mass within which either picrolite or chrysotile may appear, or within which both may be coextensive. The conditions that have prescribed the appearance of one, or the other, or of both, are not clear. There may be a distinct age relationship. Picrolite is confined to the margins of the ultrabasic body, close to confining faults. The ore bodies and the picrolite-bearing zones either do not outcrop, or show only a few square feet (less than a thousand) clear of soil and overburden.

The host-rock has been a pyroxene-rich peridotite (more than 50 percent nacreous enstatite). As a result of regional studies it has been suggested that the intrusive is part of an island-wide sill, or a series of sills. Some evidence within the general area points to the metamorphism of a sheet, or several sheets of submarine ultrabasic lavas. This is an absorbing geologic problem whose elucidation is far from advanced.

The mass of serpentinite, within which the main mineral bodies exist, had been at one time deeply buried (during the formation of the chrysotile). It was subsequently raised by faulting as a horst block, or series of blocks separated by step-faulting, to the same crustal levels as the less highly altered sediments and lavas adjacent. The capping over the asbestos bodies, of pyroxene-rich peridotite, stands up as rugged outcropping bluffs at a slightly higher elevation than most of the surrounding terrain. Other and similar horst structures are known within the Burlington Peninsula and elsewhere across Newfoundland.

The ultrabasic rocks have been tightly folded and partake of the regional plunge of the sedimentary structures, i.e., to the north-northeast at an angle of less than 45 degrees. The unfaulted ultrabasic contacts, as well as the fiber-bearing zones, parallel this regional plunge. Where affected by faulting, as at the margins of this and other horst blocks, the dip of the contact, and of the fiber-bearing zones is steeper than 45 degrees (in a direction away from and normal to the contact).

The faulted margins of the horst blocks, and any fiber-bearing or picrolite-bearing zones in their vicinity and near surface form marked erosional lows in the topography. Glaciation has been effective in dropping a drift debris of boulders, sand, gravel and interspersed clay in these depressions, to the obscuration of the ore and of the intimate structural details of the contacts.

Preliminary studies of the peridotite petrofabric have revealed a preferred orientation of the pyroxene (enstatite) relicts. The original enstatite crystals have been corroded and resorbed during the ultrametamorphic processes that have changed the mass of the peridotite into serpentinite. During or before

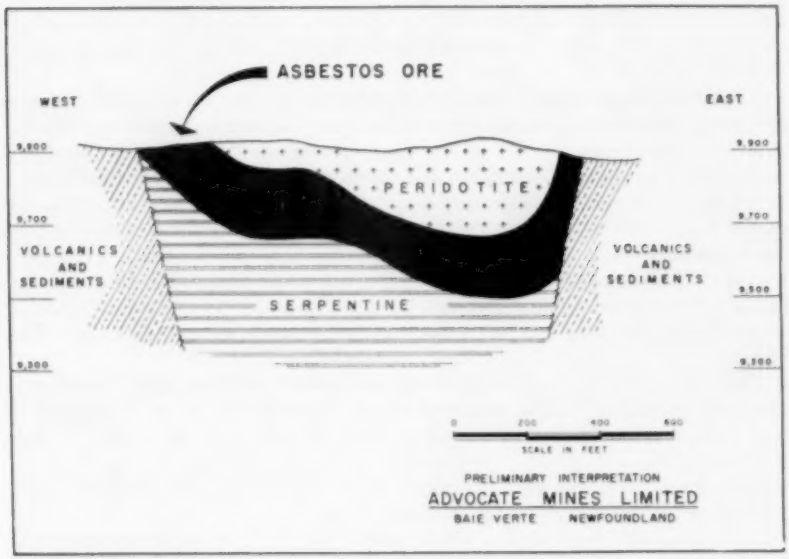


FIG. 1. Generalized cross-section of the ore zone, Advocate Mines Limited. (*Derived December 1956 by W. James Bichan, resident geologist former Falconbridge concession: 1956–59.*)

this process the relict pyroxenes (skeletal crystals of enstatite) have become oriented sympathetically with one another through intra-crustal pressure. The result is that their tabular habit is normal to the pressure that induced this orientation grouping.

Analysis of the attitudes and directions of the components of the joint-fracturing pattern shows that this bears a definite relationship to the orientation direction of the relict pyroxenes. This is consistent with their origination as a complementary set of shear joints, two or more sets of tension joints oriented at right angles to the planar alignment of the relict enstatite, and paralleling the opposing directions of the confining pressures.

A study of the proportional distribution of the tension joints by their attitudes in relation to a horizontal datum plane has not been completed. There is variability as between the different sections of the intrusive (or extrusive) ultrabasic bodies, influenced either by the contact relationships or the local directions of easiest release of pressure.

A simple linear relationship has been determined empirically between the percentage of fiber and the number of directions of veining present in any given five-foot section of ore. The statistics for this study were taken from the records of visual estimation of the fiber content of the drill cores.

The foregoing notes are presented pending an exhaustive study of the orebodies of Advocate Mines Limited. These contain an aggregate estimated worth in chrysotile exceeding a quarter of a billion dollars, within the more than 30 million tons of open-pit ore that have been delineated by drilling.

MINERAL ASSOCIATES LIMITED,
TORONTO, CANADA.
January 4, 1960

SUPPLEMENT TO VADEMECUM OF THE RUSSIAN GEOLOGICAL PERIODICALS[1]

EUGENE A. ALEXANDROV

Name of the periodical	Subjects covered
GEOLOGIYA RUDNYKH MESTOROZHDENIY (Geology of Ore Deposits). Published by the Academy of Science of the USSR since January 1959. There are 6 issues per annum. Each issue contains about 8 major articles and 120 pages. A. G. Betekhtin is chief editor.	The principal subject covered by the journal is ore genesis. Secondarily, it is concerned with description of individual Russian ore deposits and their relation to metallogenic provinces. Mineralogy, mineragraphy, problems of structural control, and exploration methods are also discussed. Information on scientific conferences and meetings is included, giving an account of the progress of this particular branch of geology in the Soviet Union. There is an English index. The current number of published issues is 1,100.

At the present time, the American Geological Institute has started translating the earth sciences division of the Doklady Akademii Nauk SSSR and Izvestiya Akademii Nauk, geological series. Geologiya Nefti i Gaza is translated by the Review of Russian Geology. With Geokhimiya, there are now four Russian geological journals translated cover to cover in United States. The journal Razvedka Nedr is translated entirely in France.

COLUMBIA UNIVERSITY,
NEW YORK CITY,
Nov. 20, 1959

[1] See vol. 54, 1959, p. 1313–1314.

Economic Geology
Vol. 55, 1960, pp. 402–414

DISCUSSIONS

THE WHITE PINE COPPER DEPOSIT

Sir: Reno Sales (3) has offered a remarkably perceptive discussion of the paper by Wright and myself (6) on the White Pine copper deposit. Ira B. Joralemon has added a brief postscript (2) more or less endorsing Sales' views and calling attention to additional data. My reply can hardly be expected to prove the origin of the deposit, but perhaps it will show how many problems one must overlook or oversimplify to be satisfied with the conclusion that the deposit was formed in one episode by hydrothermal solutions of magmatic origin emanating from the White Pine fault.

The main thesis of our original paper was that the distribution of shale ore shows virtually complete independence of the structure and is related in almost all its aspects to the lithology and paleogeography of the host beds. From this we concluded (6, p. 713) that "at least three general theories of origin satisfy these conditions: (1) the copper was dropped into or precipitated within the original mud; (2) the copper, diffusing downward into the uppermost few inches of mud, replaced some primary constituent of the mud, perhaps iron sulfide or calcium carbonate; (3) the copper was introduced into the rocks after lithification and presumably deformation, and the loci of deposition were controlled to an extraordinary degree by the physical or chemical character of the host rocks." At least one additional possibility, in some respects more satisfactory than any of the others, should have been added to the list: (4) the copper was introduced into the shales from below after they were buried but before they were deformed or compacted to anything like their present degree; this might be called a "diagenetic" or "cementation" hypothesis. On the basis of some relationships described below that have become apparent since our paper was written, I would favor this fourth hypothesis over the other three if it were essential to choose among them at this time.

The version of the third hypothesis that Sales espouses necessarily denies the existence of a significant copper concentration at the site of the present ore body before the deformation and faulting of the area, and in this respect differs fundamentally from the other three hypotheses. The heart of the argument, therefore, lies in this point. Sales takes issue with the arguments for a pretectonic copper concentration as follows: (a) all of our plan maps show "a close relationship areally between the [White Pine] fault fissure and the ore distribution;" (b) the existence of copper in fissures and the pattern of distribution of copper in sandstone show, as we pointed out in our original article, that at least some of the copper was emplaced after the faulting, and a hypothe-

sis involving two "periods of mineralization" is "wholly untenable;" (c) the apparent control of ore deposition by sedimentary facies and particularly the lack of control by structure and permeability, which are fundamental arguments for a pretectonic copper concentration in the shale, can, in his opinion, be explained away by a mechanism involving diffusion from sandstone beds and precipitation by carbonaceous material. I will discuss these three points in this order.

(a) Our article presented maps showing the distribution of copper in four different shale beds (6, Figs. 9, 10) and two sandstone beds (6, Fig. 11) of the cupriferous zone. We showed that the pattern of ore distribution in the sandstone is patchy, as would be expected of ore introduced after deformation, and pointed out that the major concentration of sandstone copper in both beds is restricted to one flank of the White Pine anticline, between the crest and the White Pine fault. Joralemon (2) calls attention also to concentrations of copper deep in the lower sandstone and to the copper mined in 1917–1920, which came mainly from sandstone; these concentrations are likewise restricted to the steeply inclined fold limb immediately northeast of the White Pine fault. The character and distribution of these concentrations in sandstone all suggest a relationship to structure, and the sandstone copper was therefore presumed to be mainly post-tectonic. This seemingly clearcut relation to structure was strongly contrasted with the distribution of copper in shale, which extends from the White Pine fault up over the crest of the anticline, and then for at least two miles down the opposite flank; the relatively uniform distribution of copper in shale, furthermore, is in marked contrast to the patchiness in the sandstone. Sales does not attempt to explain these contrasts, but argues directly from the post-tectonic character of one distribution that all the distributions must be post-tectonic.

His statement that all the maps show a relationship between ore and the White Pine fault is, at the very least, stretching a point when applied to the maps showing copper in shale. It is true that the richest part of the lowest copper-shale bed is near the fault, and that the grade seems to decrease gradually for 2–3 miles away from it. As he clearly recognizes, however, the same relationships could just as well result from offset of a pretectonic ore body by the fault. This latter explanation requires that the ore body continue on the opposite side of the fault, and there has, needless to say, been considerable informal speculation on the possibility for some time, but more exploration will be needed before the question is answered. If the pattern of copper distribution southwest of the fault should prove to be consistent with the hypothesis that a prefaulting ore body has been offset, this fact will argue for the existence of a pretectonic copper concentration almost as strongly as a lack of ore southwest of the fault would argue against it. The important point will be whether or not the pattern of copper distribution matches across the fault, and not whether the grade increases or decreases away from the fault, as Sales implies.

The diagrams for the copper content in the three higher shale layers (6, Figs. 10B-D) show high points and low points both near and far from the

fault, and if there is a "close relationship areally" between fault and copper in these beds, it certainly is far from obvious.

(b) Sales' objection to two episodes of mineralization seems to be based on the presumption that the post-tectonic copper in fissures and sandstone had to come from some source outside the deposit. He completely ignores the likelihood that the shale might be the source of the copper in the second "period of mineralization" that he decries so heartily as part of a hypothesis that is "wholly untenable." Such a hypothesis is certainly not "untenable." One may cite the hydrocarbon of the Nonesuch shale as a clearcut example of a remobilized constituent. Hydrocarbon is very finely disseminated in the shales, and occurs in somewhat larger blebs or masses both in the interstices of sandstone (where it is later than chlorite) and in the joints, veins, and faults that cut the rock—relationships identical in all respects with those shown by the copper minerals. One would hardly conclude from this that the hydrocarbon was introduced into the shale from the faults.

Joralemon (2) says that if there has been "solution, migration, and redeposition of the copper subsequent to its original deposition," the migration must have been extensive. This conclusion is debatable. The total copper produced from the old White Pine mine, mainly from sandstone, amounted to less than 10,000 tons. Even if it be granted that the total copper in sandstone, including that in beds well below the parting shale, amounts to as much as 20 or 30 times this sum, the total is small compared with the published reserves of more than 3,000,000 tons of copper for the deposit as a whole. It should also be noted that nothing in either the syngenetic or diagenetic theories precludes the existence of some copper in sandstone before faulting.

From the point of view of redistribution, the quantitative importance of copper in fractures is more difficult to evaluate. If the copper were introduced along the veins from a remote source, one might expect areas with numerous veins to contain more copper than those without veins; conversely, if the copper in the veins accumulated by lateral secretion from the immediately adjoining shale walls, one would expect the abundance of copper and its stratigraphic distribution in a given block of ground to be little affected by the presence of veins. In general the latter situation seems to hold (6, p. 708–712), although no one has yet carried out detailed sampling designed specifically to settle the question. A study of the distribution of copper isotopes made for this purpose (5, p. 186 189) was inconclusive.

In short, some of the copper at White Pine has unquestionably reached its present resting place since the rocks were deformed, but Joralemon's forceful phraseology gives a very exaggerated impression of the proportion of copper that has demonstrably moved more than a few inches since deformation.

Sales argues reasonably enough that if there are two episodes of copper deposition, it should be possible to find "demonstrable differences in the kinds and space relationships of the copper minerals in the ore." Differences in kind and space relationships of the copper minerals do exist; pyrite or chalcopyrite occurs in veins cutting chalcocitic shale in the heart of the ore zone; bornite-chalcopyrite veinlets locally cut the parting shale and also pyritic

shale just above the ore zone; E. L. Ohle, Chief Geologist at White Pine, has recently shown me specimens with border zones 1 to 6 inches wide next to chalcocite veinlets—the border zones contain only chalcocite, in contrast to the rock beyond, which contains both chalcocite and native copper; chalcocite can be found in pseudomorphs after pyrite at the top of the ore body. Though all these things suggest sequences of events, they do not provide evidence for the time gaps, if any, within the sequences. It is easy enough to identify the copper minerals in cracks (the third element in Joralemon's discussion) as postfracturing, but inasmuch as the great bulk of the copper minerals are finely disseminated in shale without any demonstrable relation to cracks, the real problem is to find irrefutable criteria for dating the finely disseminated copper minerals away from cracks. Despite considerable search, I have seen nothing myself in outcrops, mine faces, or drill core, megascopically or microscopically, that would prove beyond doubt that copper minerals were or were not present before the faulting. Too much depends on the powers one will grant to the process of replacement. The kind of problem one faces is represented by our discussion of chalcocite nodules (6, p. 702). It is quite likely that some of the investigations now being carried out at White Pine will provide the kinds of proof that are needed, but this remains to be seen.

(c) The most compelling arguments in favor of the existence of a pretectonic copper concentration are the following. (1) The striking contrast between the distribution of copper in sandstone and that in shale, both in area and character, has been noted above. (2) That fractures have apparently played a very minor role is shown by lack of correlation between shale-ore distribution and the abundance of faults and fissures (6, p. 708–712). (3) The stratigraphic position of the top of the ore zone is extremely regular over wide areas, and is apparently independent of fissures. If fissures played any significant part in the ore distribution, one should find widespread evidence for mantos on the numerous favorable—i.e., carbonaceous, thinly laminated—beds well above the ore zone. (4) Finally there is the problem of why, unless driven by an overpowering faith, solutions should ever choose a path that goes up over the crest of an anticline and then more than two miles down the other limb, for a drop of 1,000 feet, instead of taking a path to the surface up the plunging crest of the anticline.

These arguments pose very real objections to a post-tectonic origin for all the copper, but Sales does not meet them directly. By way of answer, he only suggests a mechanism that explains in general terms why the loci of deposition might seem to be independent of structure. He proposes that the copper has been introduced into the shale largely by diffusion from adjoining sandstone aquifers, and that it has precipitated there in certain layers as a result of their higher carbon content. Since lithology and carbon content are determined primarily by the paleogeography of the environment in which the host rocks were laid down, it is natural that the distribution of the copper should show an intimate relationship to lithofacies. This is a reasonable enough hypothesis and something like this may well have taken place

at some time in the history of the deposit, but it does not meet the specific objections to post-tectonic shale copper posed in the foregoing paragraph, possibly excepting the second. Scrutiny of the mechanism that Sales proposes will reveal that it emphasizes the sandstone beds and not the fissures, the lithology of the host rock and not the structure. The only tectonic feature that remains as an essential part of his hypothesis is the White Pine fault, and with 1,000 feet or more of permeable sandstone and conglomerate beneath the Nonesuch shale, one may reasonably inquire why even that is needed. The necessity of explaining the shale copper by a mechanism that would work as well or better without the faults and fold reveals the weakness of the case for making all the copper post-tectonic.

Two minor aspects of Sales' discussion deserve comment. (1) The coexistence of chalcocite and native copper tells us little, if anything, about the origin of the deposit—copper and chalcocite are almost certainly stable together in a range of environments that would include both the sedimentary and epithermal. The proportions of the two would be governed by the partial pressure of sulfur, and in a low-sulfur environment, native copper could predominate.

The role of hematite in reducing copper-sulfide solutions is open to question. That chalcocite and hematite are stable together in the environment of these deposits is shown by fairly common selvages of earthy hematite around chalcocite nodules, with no intervening native copper. Crystalline hematite and chalcocite also occur in close proximity, at least, in veins in native copper deposits in lava 50 miles east of White Pine.

(2) Dr. Sales notes that "although a large body of quartz porphyry occurs within a few miles of the mine area, the authors fail to mention it as a possible source for the sandstone copper." There are, indeed, bodies of rhyolite both west (in the Porcupine Mountains) and south of White Pine, though relatively little of this rhyolite, particularly in the Porcupine Mountains, could properly be called quartz porphyry. The age of these rhyolites is most critical: if they antedate the Nonesuch shale, they obviously cannot be a source of epigenetic copper in that formation. Evidence bearing on this point may be briefly summarized as follows.

The typical rhyolites of the region are all interstratified with or intrusive into rocks older than the Nonesuch shale. Although relatively little has been done on these rocks, partly because they are poorly exposed, the geologists (including the most recent investigator (4)) who have actually studied them in the field have interpreted many, if not most, of the rhyolites of the region as flows and groups of flows in the upper part of the Middle Keweenawan lava series. The so-called "Chippewa felsite" can be traced as a stratigraphic unit for many miles. One the other hand, much of the rhyolite in the area south of White Pine and at least a little of the rhyolite in the Porcupine Mountains is definitely intrusive into both the rhyolitic and mafic lava flows. It does not typically invade the rocks immediately below the Nonesuch shale, although I did find one small rhyolite dike cutting conglomerate only a hundred

feet or so below the shale in an outcrop seven miles east-southeast of White Pine. The only rhyolite known to cut rocks above the Nonesuch shale in the region is 6 miles north of Hancock, Michigan (1), 56 miles from White Pine, but this is biotitic and strikingly different from the other rhyolites of the region. There is, therefore, nothing to show irrefutably that the rhyolites are or are not all older than the Nonesuch shale.

The authors of Professional Paper 144, who favored a magmatic hydrothermal origin for the White Pine deposit, naturally interpreted the rhyolite of the Porcupine Mountains as a post-Nonesuch intrusion; their only evidence for this view is the domelike shape of the body and the pattern of faults in the surrounding terrain (the White Pine fault is one of these), both of which suggested to them the possibility that the body is essentially laccolithic. It may be pointed out in opposition to this view that most of the rhyolites of this complex are (or were) glassy, and much finer grained than would be expected in a laccolith at least 12 miles long and 4 miles wide, intruded beneath a sedimentary cover many thousands of feet thick.

The following evidence favors an earlier date for the intrusive rhyolite. (a) The presence of exceptional amounts of both intrusive and extrusive rhyolite suggests a connection between the two, and if they represent the identical period of igneous activity, most and possibly all of the intrusive rhyolite antedates the deposition of the Nonesuch shale. (b) The great abundance of rhyolite fragments in the Keweenawan rocks in and below the Nonesuch shale likewise suggests that the great period of rhyolite intrusion and extrusion was pre-Nonesuch.

It might be further pointed out that the later the ore deposit, the more remote the possibility that it has any connection with the Keweenawan rhyolites. Since beds thousands of feet above the Nonesuch shale were involved in the faulting and folding of the area, a connection between ore deposition and rhyolites is far more compatible with a syngenetic or early diagenetic origin than with a post-tectonic epigenetic origin.

To sum up, therefore, important stumbling blocks remain in the path of the "simple" hypothesis that all the ore is post-tectonic, and it was the existence of these obstacles that led us to favor a more complex origin in our original article. A more complex origin still seems essential, but as indicated at the beginning of this discussion, we did fail to consider an alternative that seems to fit the facts of which I am now aware better than either a syngenetic or a post-tectonic epigenetic origin.

Since our paper was written, the White Pine deposit has been opened up, and a great deal of further exploration and study has been carried out by mining companies on the Nonesuch shale both at White Pine and farther east and west. Though not an active participant in these undertakings, I have been fortunate in the opportunities given me to examine drill core, drill logs, and underground openings, for which I wish to thank geologists and officers of the White Pine Copper Co., U. S. Metals Refining Co., and Bear Creek Mining Co. It has become increasingly apparent that the top of the cupriferous zone is a fairly sharp boundary, both at White Pine and elsewhere, and

that all the dark-colored carbonaceous beds below this boundary are cupriferous, to some extent in proportion to their blackness, whereas those above it have only the traces of copper one might expect in any black shale. The boundary does not fall in the same bed everywhere, as Figure 5 of our original article (6, p. 686) shows, but over lateral distances measured in thousands of feet or miles gradually but very definitely transgresses up or down stratigraphically. Microscopic study of drill core from the boundary has shown the existence of clearcut vertical zoning, with the sequence, in ascending order, chalcocite-bornite-chalcopyrite-pyrite. This zoning is very abrupt, commonly occurring in the space of 1 to 6 inches. Each zone contains finely disseminated grains of its characteristic mineral and the transition zones contain two minerals. An unusual feature of the zoning is the fairly common occurrence of minute traces of greenockite (CdS) in the lowermost pyritic bed above the cupriferous zone. Megascopically, at least, many drill holes do not show the complete sequence of zones—one dark-colored bed with only disseminated pyrite may lie several feet or even tens of feet above the next dark-colored bed, and this lower bed may contain only chalcocite; no bornite or chalcopyrite will be found below a bed with disseminated chalcocite, however, except in veins, or possibly at the very bottom of the cupriferous zone.

These relationships are not what one would expect in an unaltered syngenetic ore body, in which the mineralogy of each layer would be determined primarily by the bottom conditions at some particular time. Within such an ore body, one would expect to find a scattering of layers of differing mineralogy throughout the section, representing oscillation of bottom environments. Although there might well be some gross trend on the scale of that of the Roan Antelope deposit, there should not be just one sharp zoned selvage, without evidence of oscillations, marking the limit of the ore body.

Another still more critical facet of this problem is the apparent lack of copper-bearing layers among the numerous dark carbonaceous shale beds in the 600 feet of strata above the cupriferous zone; many of these are lithologically identical with beds in the copper-bearing zone. Though it is always risky to say that something is absent, I have examined a number of complete drill sections of the Nonesuch shale, paying particular attention to the darker layers, and feel quite sure that there are no cupriferous layers above the cupriferous zone. (There is not even very much pyrite in most of these layers.) Such assays as have been made of the rocks above the cupriferous zone support this view. If the copper came directly from the lake or sea in which the shale was deposited, it is very difficult to explain how practically all the copper came to be deposited in the basal 4 to 5 percent of the Nonesuch shale, with no recurrences of copper deposition in the beds higher up. On the other hand, the relationships are quite compatible with the possibility that the copper was introduced into the shale from the immediately underlying sandstone. The top of the ore body in any vertical section would, under this hypothesis, simply represent the place where the last copper was removed from solutions moving generally upward through the shale, and no copper would be expected higher in the section.

For these reasons, it seems necessary to conclude that the bulk of the copper arrived after the uppermost cupriferous beds were in place and perhaps covered by several tens or even hundreds of feet of overlying beds. But the arguments for pretectonic copper make it likely that this introduction of copper took place before the rocks were deformed. Because the permeability of the shales and the chemical activity of the organic matter would both decrease rapidly with time and burial, the earlier the origin, the more readily is it explained. Chalcocite locally forms nodules and also is finely disseminated in some calcareous nodules; the bedding is deflected around these nodules suggesting that they appreciably antedate the present state of compaction. Though these relationships are not compelling, they do conform readily with the hypothesis that the copper was already present during the early stages of compaction and diagenesis.

Where did the copper come from and how did it get there? These critical questions cannot be answered except by hypothesis that is almost as tenuous as the late-epigenetic theory. One who has worked in the region cannot fail to be impressed by the enormous extent of the area in which copper is almost universally present at the base of the Nonesuch shale. This area is at least 100 miles long and 10 miles wide (6, p. 715). The size of the area suggests a widespread rather than a local agent of copper distribution, even though there are great differences from place to place in the actual concentration of copper. The kind of regional movements of connate water that must take place when a large sedimentary prism is compacted would satisfy the implications of both the widespread distribution of copper and the evidence that copper was present fairly early in the compaction process. The role of diffusion and particularly the causes of deposition that Dr. Sales has suggested may well have been important, and it can hardly be doubted that these activities would proceed more readily in only partially compacted sediments than in lithified and deformed sediments.

The still more speculative question of how the copper got into this connate water in the first place is best left open at this time.

To conclude on a more philosophical plane, Dr. Sales seems to argue, particularly in his next to last paragraph, that an explanation that is simple and understandable is ipso facto more credible. The merits of associating simplicity and credibility are certainly dubious. But even granting a relationship, when two deposits are as different as White Pine and Butte, is it not actually simpler to infer entirely different origins than to attempt to force both into the same mold? Reducing all nonferrous metal deposits to the common denominator of a fault or favorable bed or both, plus an igneous rock, seems like a rather extreme oversimplification.

WALTER S. WHITE

U. S. GEOLOGICAL SURVEY,
BELTSVILLE, MARYLAND,
Dec. 5, 1959

REFERENCES

1. Cornwall, H. R., and Wright, J. C., 1956, Geologic map of the Hancock quadrangle, Michigan: U. S. Geol. Survey, Mineral Investigations Field Studies Map MF-46.
2. Joralemon, I. B., 1959, The White Pine copper deposit: Econ. Geol., v. 54, p. 1127.
3. Sales, R. H., 1959, The White Pine copper deposit: Econ. Geol., v. 54, p. 947–951.
4. Thaden, R. E., 1950, The Porcupine Mountain red rock: Unpublished Master's thesis, Michigan State University.
5. Walker, E. S., Cuttitta, F., and Senftle, F. E., 1958, Some natural variations in the relative abundance of copper isotopes: Geochim. et Cosmochim. Acta, v. 15, p. 183–194.
6. White, W. S., and Wright, J. C., 1954, The White Pine copper deposit, Ontonagon County, Michigan: Econ. Geol., v. 49, p. 675–716.

HURONIAN URANIFEROUS CONGLOMERATES[1]

Sir: C. F. Davidson is indefatigable in his efforts to show that it is unlikely that uranium in Witwatersrand and Huronian conglomerates could have been of placer derivation. Many if not most of his arguments have the following theme in common: *if the uranium is of placer origin then the deposits and the sedimentary rocks that contain them are extremely unusual if not unique.* It is hard to see how this approach can be very helpful in answering the burning question: "How did the uranium get there?" We know that both the Witwatersrand and Huronian stratigraphic sequences represent unusual assemblages of rocks and that it is hard to duplicate them anywhere in the world in rocks of any age. Apparently, such sedimentary sequences are formed under uncommon conditions, and if formed they are seldom long preserved. We also know that uranium deposits of the Huronian and Witwatersrand types are rare (even though they contain much of the world's uranium ore reserves) and in fact have only been found in rocks that are probably almost 2 billion years old. Whether the deposits are of epigenetic origin or of placer derivation, they were obviously formed under combinations of conditions that are so unusual that they are not known to have recurred on an important scale during the last billion years or more.

In a recent discussion (1) Davidson has emphasized "two fundamental geochemical criteria whereby the banket ores of the Witwatersrand, Blind River, and elsewhere can be distinguished from radioactive mineralization of unquestioned detrital origin." He seems to imply that the "criteria," or standards of reference, are based not only on consistent analytical data but also on chemical and physical laws. It is unfortunate that such a conclusive "criterion" must be defined as vaguely as his first one: "First in the Witwatersrand-type formations the highest uranium content is almost always associated with the country rock sediments of coarsest grain size, this being the antithesis of the distribution pattern habitually found in the radioactivity logging of younger strata." Why does he imply that radioactivity logs of bore-holes constitute measurements of variations of uranium contents in different rocks through the sequences drilled when he is well aware (2, p. 689) that "these give no precise quantitative measurement of the uranium content of the strata"? As a matter of fact, less than one-quarter of the radioactivity

[1] Published by permission of the Director, Geological Survey of Canada.

in an average shale is due to uranium (3, p. 423) and less than one-half in most sand-size sediments. Had Davidson investigated thoroughly, he might have found cases where coarse-grained sediments ("granite wash") intersected in holes drilled for petroleum are *more* radioactive than associated fine-grained sediments, and situations, such as the Gulf Coast, where natural radioactivity logs are commonly of little use in distinguishing shales because of the comparable radioactivity of heavy mineral-bearing sandstones in the sequence.

Very few sediments of sand and gravel size have been analyzed for both uranium and thorium contents. This includes "radioactive mineralization of unquestioned detrital origin" because the general practice in economic examinations of such material is to measure radiometrically its *equivalent* uranium *or* thorium content rather than to make accurate analyses for both uranium *and* thorium. There is at least one case on record where sandstone contains more uranium and has a lower Th : U ratio than associated shale (3, p. 398 and 399—Pennsylvanian age, Brownwood C. Texas). There are other analyses of sandstones that have lower Th : U ratios than associated shales (3). This denies the thesis that uranium *always* shows a preferential association with shale in contrast to thorium which is preferentially associated with resistate-bearing sands. Many minerals with Th : U ratios less than one occur as detrital grains concentrated in sands and gravels. Some low-grade ones, like zircon, are common. Other highly radioactive ones, including brannerite and thorian uraninite, are rare but nevertheless have been found in a fair number of occurrences. In most occurrences of detrital uranium-bearing minerals, thorium-bearing minerals, such as monazite, allanite, thorite and thorianite, are present in sufficient quantity to result in the overall thorium content exceeding that of uranium. This, however, is simply a statistically probable relationship controlled by relative abundances and grain sizes of minerals in average source material. It is not a proper basis for a *criterion;* exceptions are obviously not only possible, but likely to be found locally within a small proportion of radioactive detrital deposits. It is of interest to note that Th : U ratios in Huronian pyritic, radioactive conglomerates are only locally less than unity (4).

Davidson's attempt to prove that Witwatersrand uraninite grains are much too small to have been deposited with the quartz grains is fallacious because Stokes' Law cannot be applied in this way to coarse, current-deposited sands and gravels. Heavy minerals found in such sands and gravels are considerably smaller ("hydraulic equivalent sizes") than would be predicted by Stokes' Law of settling velocities (5, 6). Heavy minerals in Huronian conglomerates and quartzites show striking consistancies in their size ranges (7, 8). The following "co-existant" minerals, for example, are listed in order of increasing sizes: uraninite, uranothorite, brannerite, monazite, certain types of anhedral pyrite grains, and "brannerite"-bearing titaniferous grains. This is also the order of decreasing specific gravities. The average size disparities between the different species can be shown to be similar to differences in the hydraulic equivalent sizes that would be expected in fluvial deposits. Slight decreases in average sizes of grains in the downstream direction correspond to more

obvious decreases in sizes of quartz pebbles (8) and are accompanied by changes in proportions of minerals present—fewer grains of heavy uraninite, brannerite, and large titaniferous compounds, more of lighter monazite and zircon (9).

Contrary to Davidson's interpretation of my earlier discussion on thorium: uranium ratios at Blind River (4), I did not reverse his second criterion (*deposits that contain more uranium than thorium are syngenetic*) and thus attempt to show that since thorium was commonly in excess of uranium in Blind River conglomerates, the deposits must be of syngenetic origin. I did not accept the criterion, or reject it, or reverse it, or express a belief that the uranium deposits were of syngenetic origin. I merely pointed out that anyone interested in the origin of Blind River uraniferous conglomerates should have long been aware that most quartz-pebble conglomerates, not only in the region, but also in the immediate vicinity of the ore deposits, contain more thorium than uranium. I also reiterated the established fact that conglomerates and quartzites with varying $ThO_2 : U_3O_8$ ratios (as high as 4.0) are interbedded within ore zones (7, p. 481). Davidson's claim that he adequately acknowledged the existence of thorium-rich conglomerates in the Blind River area by making reference to monazite deposits 200 miles away in rocks that cannot even be correlated with the Huronian in Ontario is hardly worth a comment. Also his suggestion that the thorium mineralization could be a "hypothermal phase zoned around the mesothermal uranium mineralization" represents a complete disregard of well-established spatial, geological, mineralogical and metamorphic relationships (4, 7, 8, 9).

Davidson unfortunately conveys the impression that it has been demonstrated, in some unspecified way, that in the Blind River area there is a "consistent sympathetic association of the heavy uraninite with the much lighter pyrite and (an) antipathetic relationship of pyrite to the equiponderant monazite." This revelation is so baseless that I hesitate to repeat it even for purposes of refutation. It has been clearly indicated in many descriptions of Blind River deposits that, although pyrite is generally more abundant in highly radioactive than in weakly radioactive conglomerates, there is no positive correlation between pyrite content and uranium content. It should be obvious also from the literature that uraninite is not the most important ore mineral in all ores, and that it is actually a rare mineral in most of the *pyritic* radioactive conglomerates of the region. No writer has reported that pyrite is more abundant per pound of U_3O_8 in uraninite ore than in brannerite ore, or in monazite-rich ore and conglomerate. As a matter of fact, pyrite : U_3O_8 ratios are lower in most uraninite-rich ores than in other ores and are highest beyond the margins of ore bodies in monazite-bearing conglomerates, which may contain as much pyrite as ore conglomerates, but no detectable uraninite or brannerite.

The abundance of pyrite relative to any one or all of the many radioactive and non-radioactive heavy minerals in Blind River conglomerates is markedly erratic and this relationship could be considered consistent with a theory that the pyrite is of multi-genetic origin. Associations of other minerals show

more consistent relationships, although even these are sufficiently erratic that the data—measurements of mineral abundances, grain size measurements, and chemical analyses—must be abundant before a systematic pattern can be discerned with demonstrable statistical confidence. This is a phenomenon perhaps more characteristic of detrital sedimentary rocks than of hydrothermal mineral deposits. In so far as I have been able to fulfill the exacting requirements of a study of variations in mineral associations, the pattern of these variations certainly appears to be one that could readily be explained by hydraulic separation of lighter heavy minerals from heavier ones and smaller minerals from those that were available in larger grain sizes. Presentation of these data and consideration of whether or not they preclude any possibility that the bulk of the uranium is of epigenetic origin are obviously neither possible nor necessary here.

Perhaps Davidson bases both his statement concerning an antipathetic relationship between pyrite and monazite and his anticipation that I may "proceed to 'hydrothermalize' the pyrite at Blind River" on the existence of hematite-ilmenite-magnetite-monazite-zircon-thorite-bearing conglomerates in the Lorrain formation 12 miles north of the Elliot Lake deposits (5). I wonder, incidently, what he might do with the information that there is a very unusual deposit 90 miles northeast of Elliot Lake that contains an ilmenite-zircon-uraninite association. It is asked: "But if the pyrite is hydrothermal, why not the uraninite also?" There is conclusive direct evidence that pyrite is *in part* a secondary mineral in the conglomerates. Surely no objective student would interpret this fact as evidence that other minerals in the conglomerate—uraninite, brannerite, monazite, rutile, uranothorite, zircon, chromite, cassiterite, quartz and feldspar, for example—are necessarily of hydrothermal origin. Pyrite is common as an epigenetic mineral in slightly metamorphosed rocks, like those at Blind River, but uraninite containing a high thorium and high rare-earth content has never to my knowledge been reported as a definite epigenetic mineral in such slightly metamorphosed rocks, nor have the other principal radioactive minerals.

It seems worth while to re-emphasize a point that has been ignored by many writers. The Elliot Lake (Blind River) deposits in virtually unmetamorphosed rocks cannot conceivably be high intensity hydrothermal deposits. The mineral associations are anomalous for low intensity hydrothermal deposits; moreover there is no country rock alteration associated with the uranium mineralization (except very locally and incidentally) nor any evidence of introduction of gangue minerals or significant trace elements (9).

S. M. Roscoe

Geological Survey of Canada,
Ottawa, Canada.
January 18, 1960

REFERENCES

1. Davidson, C. F., 1959, Further observations on uraniferous conglomerates: Econ. Geol., v. 54, p. 1316–1320.
2. Davidson, C. F., 1957, On the occurrence of uranium in ancient conglomerates: Econ. Geol., v. 52, p. 668–693.

3. Adams, J. A. S., and Weaver, C. E., 1958, Thorium to uranium ratios as indicators of sedimentary processes: example of concept of geochemical facies: Am. Assoc. Petroleum Geologists Bull., v. 42, p. 387–430.
4. Roscoe, S. M., 1959, On thorium-uranium ratios in conglomerates and associated rocks near Blind River, Ontario: Econ. Geol., v. 54, p. 511–512.
5. Rittenhouse, G., 1943, Transportation and deposition of heavy minerals: Geol. Soc. America Bull., v. 54, p. 1725–1780.
6. Sundborg, A., 1956, The River Klaralvan a study of fluvial processes: Geografiscka Ann., 38.
7. Roscoe, S. M., and Steacy, H. R., 1958, On the geology and radioactive deposits of the Blind River region: Trans. Second Intern. Conf. on Atomic Energy, Geneva, v. 2, p. 474–483.
8. Pienaar, P. J., 1958, Stratigraphy, petrography and genesis of the Elliot group including the uraniferous conglomerates, Quirke Lake Syncline, Blind River area, Ontario: Ph.D. thesis, Queen's University, Kingston, Ontario.
9. Roscoe, S. M., 1959, Monazite as an ore mineral in Elliot Lake uranium ores: Canadian Min. Jour., July, 1959.

Economic Geology
Vol. 55, 1960, pp. 415–418

REVIEWS

New Zealand Coals, Their Geological Setting and Its Influence on Their Properties. By R. P. SUGGATE. Pp. 112. New Zealand Department of Scientific and Industrial Research, Bulletin, 134, 1959. Price, 12s. 6d.

The main objective of the investigation upon which this report is based was "to obtain the maximum amount of information from the proximate and ultimate analyses, and in particular to relate differences in analysis to differences in the geological settings of the samples." A second objective was "to discuss properties of the coals such as calorific value and crucible swelling number in relation to the analyses." The accomplishment of these objectives is attended by critical consideration of many of the fundamental proceedings used in handling conventional coal analyses in order to achieve values upon which geological interpretations of such analyses can be safely based. The unusual procedures employed in handling the analytical data will be of interest to coal geologists and coal geochemists.

The introductory chapter points out that New Zealand coal, which are all of Cretaceous or Tertiary age and which extend in rank from lignite to semianthracite, "do not easily fit any classification devised for overseas coals." The report consists very largely of setting up a scheme of classification, particularly rank classification, such as is regarded suitable for these coals and capable of correlation with overseas classifications, on the basis of carbon, hydrogen, volatile matter, and calorific values with special consideration given to sulfur and nitrogen. The first chapter also provides general information concerning the geological setting of the New Zealand coal beds with brief reference to their macroscopic aspect, viz., the dull appearance of the lignites and the bright banded character of the higher rank coals. These latter consist mainly of vitrain and clarain. Fusain is relatively rare but exinite, particularly resinite, is quite common. Petrographic, paleobotanical, and chemical work has been carried on since about 1930 but mainly in the past 10 years.

The remaining eleven chapters report the methods of handling the data provided by proximate and ultimate analyses, the crucible swelling number, a few ash analyses, and analyses of weathered coal to arrive at a method of establishing what S. calls "absolute rank" of a coal, with appropriate differentiation of coals of the same rank on the basis of coal type. As a "significant indicator of type" (p. 37), much importance is placed upon the nitrogen content of coal.

The list of items used in the classification of the selected 140 New Zealand coals (Table 6) is somewhat impressive and consists of the following: proximate values, sulfur and Btu, on an air-dried basis; ultimate values, volatile matter, and calorific value on a dry ash-free basis; carbon and hydrogen each on a N-free basis; calculated volatile matter and calorific value and the difference between calculated and determined values for both items; sulfur-free volatile matter and calorific value; rank as determined from carbon and hydrogen values and also from volatile matter and calorific values and the average of the two, designated as "adopted rank." The list includes a number of unfamiliar values or parameters, the meaning and determination of which are explained in the text.

The H and C values used provide the basis for establishing the position of a "coal band" for New Zealand coals somewhat different from that prepared by Sayler and others for overseas, mainly Carboniferous, coals. Adjusted volatile matter and calorific values are then superimposed in a grid over the coal band after the methods of Seyler, Francis, and others. This makes it possible to arrive at values for "calculated" volatile matter and calorific values, although calorific value can also be determined by use of a modified Dulong type of formula. Suggate holds that depth of burial is the most important influence in determining rank and suggests (p. 91) that a "standard sequence indicating the effects of depth of burial is desirable." To this end he provides a chart indicating variations in H', C, calorific value, and volatile matter as determined by depth of burial. "The most convenient way or referring to a coal of 'the rank attained by being buried 19,000 ft. is to describe it as being of 'rank 19.'"

The use made of crucible swelling members (Chapter 8) is based upon the proposition that the swelling powers of coal, first developed in lowest rank bituminous coal, increases slowly until medium volatile bituminous rank and then rapidly decreases (p. 59). The decrease is paralleled by an increase in porosity and a consequent tendency for moisture content to increase. "It appears that New Zealand coals begin to develop swelling properties at a slightly lower carbon contents than British coals, that the swelling properties develop more rapidly in the middle range (numbers 4 to 8), and that the coals attain far greater degree of swelling" (p. 59). "For New Zealand coals the decrease begins at 33 per cent volatiles," which may also be the case for British coals (p. 60). This is accompanied by increase in porosity. "In general coals with the lowest moisture contents (air dried coals) have the highest swelling numbers, and it has been found that where the overburden (which ranges from 1 to 1,000 ft) is shallowest the coals have, in general, the higher moisture contents."

GILBERT H. CADY

URBANA, ILLINOIS,
Nov. 18, 1959

Dana's Manual of Mineralogy, 17th Edit. Revised by CORNELIUS S. HURLBURT, JR., 1959. Pp. 609; figs. 634. John Wiley & Sons, New York, 1959. Price, $11.50.

This 17th edition of the well-known Manual of Mineralogy appears some 7 years after the 16th Edition and with 104 more pages. The general arrangement is the same, with identical section divisions, but the content of each section has undergone considerable change.

This edition reflects further the change in mineralogy from the descriptive to the quantitative. Although the descriptive has been retained, as it must in any elementary treatment of mineralogy, quantitative methods have been introduced more fully. One notices the broad use of the crystal-chemistry approach, which serves to unify the chemical, crystallographic and physical properties of minerals through fundamental structural and chemical considerations.

The second section on Crystallography is drastically changed and now includes the stereographic projection, the 32 crystal classes, rules for crystal orientation, calculation of axial ratios, and x-ray crystallography. The section on Chemical Mineralogy (4) has been adapted to a new quantitative approach and Crystal Chemistry has been added to. In section 5, Descriptive Mineralogy, a short discussion of the crystal chemistry of each class precedes the description of individual

species in that class. These changes account largely for the 104 pages of increase in size.

This new edition will greatly increase the already broad use of the Manual.

Petroleum Geology. 2nd Edit. By KENNETH K. LANDES. Pp. 443. John Wiley & Sons, New York, 1959. Price, $9.50.

Since the first edition of Professor Landes' *Petroleum Geology* appeared eight years ago rapid advances in the knowledge of petroleum geology have taken place, particularly in regard to theories on the evolution of oil and gas, and oil finding. Consequently, three-fourths of the former edition have been rewritten.

We note in this edition a new chapter on "Reservoir Seals," and extended new discussions on the origin of oil and gas and the role of fractures in the migration and storage of oil.

This second edition is much shorter than its predecessor, 443 pages as compared with 660 pages, due in part to the elimination of some chapters. The first book was divided into three parts and this edition although not so subdivided falls into three parts. The first two chapters deal with the profession of petroleum geology and with drilling, completing, and producing oil and gas wells. The next two chapters are concerned with the techniques of the petroleum geologist—exploration, and subsurface and production geology. The following ten chapters are devoted to the geologic occurrence of petroleum—origin; evolution; reservoir rocks, fluids, and seals; migration; and traps. The last chapter deals with the regional aspects of petroleum. An appendix gives the literature of petroleum geology. The last three chapters of the first edition, namely domestic and foreign distribution, and future oil supplies, have been eliminated. The "case studies" have been retained in part but in briefer form.

This edition incorporates all of the newer information on the geology of oil and gas and in its present form should make a more usable text book than its predecessor.

Structural Methods for the Exploration Geologist. By PETER C. BAGLEY. Pp. 280; figs. 329; pl. 16. Harper & Bros., New York, 1959. Price, $7.50.

The author states that this volume is designed to give a comprehensive coverage of structural geology methods and to give a demonstration of their application in exploration. It is designed for professional geologists, geophysicists, and petroleum and mining engineers. As a text for classroom use it reviews the fundamental principles of structural geology and relates them to actual field conditions.

The nine chapters are: (1) Descriptive Geology Applied to Structural Geology; (2) Outcrop Patterns; (3) Geologic Cross Sections; (4) Structure Contour Maps; (5) Isopach, Isochore, and Convergence Maps; (6) Isometric Projections and Ore Reserve Estimations; (7) Inclined Fault Problems; (8) Stereographic Projections; (9) Tectonic Analysis of Mining and Petroleum Districts as an Exploration Tool. The chapters begin with a review of principles, illustrated by case histories. Actual field problems, rather than abstract ones, are presented as simply as possible. The large page size 8×11 inches permits the use of large figures and plates. Sixteen beautiful mosaic and overlapping air photographs display remarkable structural and geomorphologic features. Forty-one different problems are presented for the student. Full references follow each chapter, and an appendix gives trigonometric functions. Mining Geologists will find the last chapter of particular interest.

The book is full of meat and certainly will prove valuable to field geologists and students.

Rock to Riches. By CHAS. H. DUNNING, with EDWARD H. PEPLOW, JR. Pp. 406. Southwest Publishing Co., Phoenix, Arizona, 1959. Price, $8.75.

This book is a story of Western America mining as exemplified in the history of mining in Arizona. The senior author graduated from Yale as a mining engineer in 1909 and has had 50 years experience in mining in the Southwest. The junior author is a trained author, historian, and journalist. The authors deal with the detailed histories of the great mines of Arizona and give analyses of the political, social, and economic factors that have determined the course of American mining during 10-year periods from prehistory to 1957.

These period discussions follow an opening chapter on "Let's Talk About Mining" given in simple language about mining practices, geology, and technical evolution. Other following chapters are Mining Today and Tomorrow, The Story in Statistics, Minor Metals and Nonmetallics, Important Arizona Mines, and a Glossary and Index.

The period discussions occupy the main body of the book. Here are recorded in story form, with much humor, the legends, the history, the developments, the personalities, and the records of production of some 65 important mines. A great amount of data is presented regarding the individual mines.

The book is of great interest to anyone interested in American mining and particularly to those who are acquainted with the Southwest. Historians also will find a wealth of material dealing with the conversion of an Indian wilderness into a great mineral producing state.

BOOKS RECEIVED

JOHN E. COTTON AND CYRUS W. FIELD

Minerals Yearbook 1958. STAFF OF THE U. S. BUREAU OF MINES. **Vol. I. Metals and Minerals (Except Fuels).** Pp. 1230. **Vol. II. Fuels.** Pp. 484. **Vol. III. Area Reports.** Pp. 1065. *Annual review of the entire mineral industry including fuels.*

Variations in Isotopic Abundances of Strontium, Calcium, and Argon and Related Topics. P. M. HURLEY, Supervisor. Pp. 240. Dept. of Geology and Geophysics, Massachusetts Institute of Technology, Cambridge, Mass., 1959. *Twenty-eight articles by staff and students dealing chiefly with ages of minerals, rocks and geologic events.*

Economics of Natural Resource Scarcity. Part I. H. J. BARNETT and CHANDLER MORSE. Pp. 147. Resources for Future, Inc., Washington, D. C., 1959. *Contemporary and historical doctrine on natural resources. Five chapters on contemporary views and social aspects; first conservation movement; Malthus; Ricardo, Mill, and Jevons; Darwin, Marsh and the conservation synthesis.*

Soil, Grass and Cancer ANDRÉ VOISIN. Translated from French by C. T. M. HERRIOT and HENRY KENNEDY. Pp. 302; figs. 17. Philosophical Library, Inc., New York, 1959. Price, $15.00. *The occurrence and distribution of minerals in the soil and their effect upon agriculture, humans and animals.*

Industrial Complex Analysis and Regional Development. WALTER ISARD, E. W. SCHOOLER, and THOMAS VIETORISZ. Pp. 294; figs. 4; many tables. Pub-

lished jointly by The Technology Press, of the Massachusetts Institute of Technology, and John Wiley & Sons, Inc., New York, 1959. *A case study analysis illustrating an analytical technique for comparing locational advantages and disadvantages in the development of a complex industry with numerous interrelated activities. The example used is the petroleum industry and its related operational phases in Puerto Rico.*

Basic Economics. L. C. MICHELON. Pp. 223. World Publishing Co., Cleveland and New York, 1960. Price, $3.75. *Basic features of American economic system. Each principle is developed in relation to one individual's daily experience. Simple and good.*

Open-Channel Hydraulics. VEN TE CHOW. Pp. 680. McGraw-Hill Book Co., New York, 1959. Price, $9.50. *Theory and practice of design for flow in open channels and related structures; practical examples, chiefly American. For students and engineers. Authoritative.*

Physik des Erdinnern, 2nd Edit. HANS HAALCK. Pp. 310; figs. 110. Akademische Verlagsgesellschaft, Leipzig, 1959. Price, DM 29. *Considerably revised. Deals with all phases of the physics of the earth's interior—content, polar rotation, gravity isostasy, strength, magnetism, seismology, spontaneous polarization, electromagnetic fields, geophysical prospecting.*

Barrages et Bassins de Retenue. Pp. 281; figs. 108; tbls. 7. Les Congrès et Colloques de l'Université de Liège, Vol. 14, Liège, 1959. *A collection of thirteen papers dealing with hydrogeological problems, such as sedimentation, in relation to dams and retention basins.*

The Geology and Mineral Resources of the Sandakan Area North Borneo. F. H. FITCH. Pp. 202; figs. 16; tbls. 21; pls. 40. Map, 1:250,000. Price M$6 or Sterling 14 shillings. Geological Survey British Territories in Borneo Memoir 9, Kuching, Sarawak, 1958. *Geology of an area composed of sedimentary, igneous, and metamorphic rocks of late Mesozoic to Cenozoic age. Deposits of chrome, coal, copper, iron, and manganese were noted but appear to be of little economic significance.*

Pliocene and Lower Pleistocene of the Western Part of the San Francisco Peninsula. WILLIAM GLEN. Pp. 147–197; pls. 3; figs. 5. Price, $1.00. University of California Publications in Geological Sciences, Vol. 36, No. 2. University of California Press, Berkeley, 1959. *Detailed lithologic and paleontologic study of the Merced formation.*

A Contribution to the Problem of the Origin of Some Chrysotile Asbestos Deposits in Eastern Asia. ZDENĚK VEJNAR. Pp. 76; pls. 16; figs. 12. Sborník Ustředního Ústavu Geologického, Svazek XXIV–1957. Praha, Czechoslovakia, 1959. *Asbestos, arising from dehydration of the serpentine gel, may occur as veinlets which fill the fissures produced by tension which in turn is produced by volume-changes during dehydration. In English.*

Directory of Georgia Mineral Producers 1959. Pp. 50; tbl. 1. Georgia Department of Mines, Mining, and Geology, Circular 2, Atlanta, 1959. *Listings are by product and county.*

Mikropaläontologische (sporenpaläontologische) Untersuchungen in der Braunkohle des Geiseltales. WILFRIED KRUTZSCH. Pp. 425; pls. 49; figs. 38; tbls. 12. Geologie, Vol. 8, No. 21/22, Akademie-Verlag, Berlin, 1959. *A micropaleontological study of spores and spore-like fossils that occur in the middle zone of the brown coal at Geiseltales, Germany. In German.*

The Economic Geology of the Stirling and Clackmannan Coalfield, Scotland. Area South of the River Forth. W. A. READ and R. B. WILSON. Pp. 73; figs. 15; tbls. 2. Price, 7 shillings. Coalfield Papers of the Geological Survey of Great Britain No. 2, Edinburgh, 1959. *Summary of the geology for this coal mining area.*

Systematic Study of So-called *Gigantopteris*. KAZUO ASAMA. Pp. 72; pls. 20; figs. 6; tbls. 14. Science Reports of the Institute of Geology and Paleontology, Tohoku University, Vol. XXXI, No. 1, Sendai, Japan, 1959. *A thorough discussion of an Upper Paleozoic fossil plant. In English.*

Forty-Seventh Annual Report by the State Inspector of Mines to the Governor of the State of New Mexico for the Year Ending June 30, 1959. W. H. HAYS. Pp. 78; tbls. 19. Office of the State Inspector of Mines, Albuquerque, 1959. *Increase in the production of copper, manganese, uranium, coal, and sand and gravel offset reduced production of lead, zinc, and perlite.*

North Dakota Has Rapid Mesozoic Facies Changes. D. E. HANSEN. Pp. 5; tbls. 2; figs. 5. (Reprinted from World Oil.) North Dakota Geological Survey Rept. of Investigation Number 34, Grand Forks, 1959. *A newly postulated gradational boundary between Jurassic and Cretaceous sediments of North Dakota suggests the possible existence of stratigraphic traps.*

The Beach Ridges of Northern Ohio. JANE L. FORSYTH. Pp. 10; figs. 5; map. Price, 25 cents. Ohio Geological Survey Information Circular No. 25, Columbus, 1959. *Correlation of beach ridges and the different glacial lake stages in this area.*

Recherche Geologique et Minerale en Polynesie Francaise. Pp. 60; pls. 24; figs. 3; tbls. 1. Maps, scale 1:15,000. L'Inspection Generale des Mines et de la Geologie de Polynesie Francaise, Paris, 1959. *Two papers: one by E. Aubert de la Rue deals with the evidence that the volcanic rocks rise directly from the sea floor and that there is an absence of granitic continental base. The second, by A. G. Obermuller, reports on a petrological study of some rocks on Clipperton Island. In French; English summary.*

The Mineral Industry of South Dakota in 1958. D. H. MULLEN and A. F. AGNEW. Pp. 13; tbls. 7. South Dakota Geological Survey Minerals Report 5, Vermillion, 1959. *Statistics for the mineral industry exclusive of mineral fuels.*

Annual Report of the Geological Survey Department 1958. Pt. I, Administrative. Pp. 19. Price, shs. 2/50. Tanganyika Geological Survey, Dar es Salaam, 1959.

Service de la Carte Géologique de l'Algérie—Alger, 1957–59.

Bull. 16. Étude Géologique de la Région des Biban (Algérie). ANDRÉ CAIRE. Volume I. Pp. 492; figs. 57; tbls. 4. Volume II. Pp. 280; figs. 92; pls. 15; maps 7. *A two-volume study dealing principally with the stratigraphy and structure of a region containing nappes of early Miocene age. In French.*

Bull. 6. I. Recherches sur la Géologie du Littoral Oranais. II. Épirogénèse et Nivellements. YVES GOURINARD. Pp. 200; figs. 33. *Pages are uncut. The first paper discusses the littoral sediments of Cenozoic age in the vicinity of Oran. The second deals with level indicatiors for epirogenic movements.*

Bull. 20. Travaux des Collaborateurs 1957. Pp. 275; figs. 13; pls. 26; tbls. 3. *Pages uncut. Ten papers dealing with various aspects of the geology of Algeria.*

Memoir 2. Goniatites Dévoniennes du Sahara. GERMAINE PETTER. Pp. 313; figs. 58; tbls. 6; pls. 26. *Pages uncut.*

Memoir 4. Vertébrés Continentaux due Miocène Supérieur de l'Afrique du Nord. CAMILLE ARAMBOURG. Pp. 159; figs. 53; pls. 18; tbls. 17. *Pages uncut.*

Bureau of Mineral Resources, Geology, and Geophysics—Melbourne, Australia, 1959.

The Australian Mineral Industry—Quarterly Review and Quarterly Statistics. Vol. 12, No. 1. Pp. 31; tbls. 15. Price, 3/–. *Review of imports, exports, and statistics of the mineral industry.*

The Australian Mineral Industry—Quarterly Review and Quarterly Statistics. Vol. 12, No. 2. Pp. 22; tbls. 12. Price, 3/–. *This number contains a paper on Australian gemstones. Gemstone production is generally incidental to the working of alluvial tin and gold deposits.*

Bull. 45. Devonian Brachiopods from the Fitzroy Basin, Western Australia. J. J. VEEVERS. Pp. 220; pls. 18; figs. 101; tbls. 3. *This study has resulted in a revision of Teichert's (1949) zonal scheme.*

Bull. 52. A Contribution to the Geology and Glaciology of the Western Part of Australian Antarctic Territory. P. W. CROHN. Pp. 103; pls. 48; figs. 15. *Report of investigations carried out in MacRobertson Land and adjoining portions of the Australian Antarctic Territory in 1955 and 1956. Traces of copper, iron, manganese, coal, and radioactive minerals have been recorded, but no mineral deposits of economic importance have been discovered.*

Bull. 55. Devonian and Carboniferous Brachiopods from North-Western Australia. J. J VEEVERS. Pp. 42; pls. 4; figs. 12; tbls. 3. *Brachiopod species have proved useful in distinguishing Upper Devonian from Lower Carboniferous rocks in north-western Australia.*

California Division of Mines—San Francisco, 1958–59.

Bull. 172. Geology and Mineral Deposits of San Fernando Quadrangle, Los Angeles County, California. G. B. OAKESHOTT. Pp. 147; pls. 5; figs. 21; tbls. 11; photos 91. Cloth binding. Price, $3.75. *Petroleum principally from the Placerita oil field is the most important economic resource. Borates, gold, and titanium ores are mined.*

Geologic Map of California Santa Cruz Sheet. Scale, 1:250,000. Price, $1.50. *One Explanatory Data Sheet and one map. Index to geologic mapping and stratigraphy.*

Geologic Map of California Santa Maria Sheet. Scale, 1:250,000. Price, $1.50. *One Explanatory Data Sheet and one map. Index to geologic mapping and stratigraphy.*

Geological Survey of Canada—Ottawa, 1959.

Bull. 54. Helicopter Operations of the Geological Survey of Canada. OFFICERS OF THE GEOLOGICAL SURVEY OF CANADA. Pp. 60; figs. 5; tbls. 9; pls. 7. Price, 75 cents. *Operational statistics and appraisals for helicopter surveys over varied terrains.*

Paper 59-4. Geophysical Interpretation of the Magnetic Anomaly at Marmora, Ontario. MARGARET E. BOWEN. Pp. 11. *Comparison of aeromagnetometer survey of magnetite deposit flown at heights of 5,000, 2,000, 1,000, 500, 400, 300, 200, and 100 feet. Very instructive.*

Geological Map of Canada 1045A. *Sheet size 30 × 32 inches. Scale, 1:7,603,200. In colors. Accompanied by separate transparent overlays of metallogenic maps with explanatory notes and special references and locality numbers for iron ore, beryllium, molybdenum and uranium in Canada.*

Bibliography of Seismology No. 3. Items 10310–10513, January–June, 1958. W. E. T. SMITH. Pp. 61–83. Price, 25 cents.

Illinois Geological Survey—Urbana, 1959.

Circ. 280. Visual Estimates of Grain Size Distribution in Some Chester Sandstones. D. H. SWANN, R. W. FISHER and M. J. WALTERS. Pp. 43; figs. 14; tbls. 4. *This is an attempt to develop a rapid semi-quantitative method for obtaining data on the distribution and size of grains in consolidated sandy rocks using a stereoscopic microscope.*

Circ. 281. Hydraulic Fracture Theory. Pt. III. Elastic Properties of Sandstone. J. M. CLEARY. Pp. 44; tbls. 10; figs. 16. *Experimental data suggests that a rough prediction of the elastic behavior for a given rock can be made on the basis of its porosity.*

Circ. 282. Chemical and Spectrochemical Analyses of Illinois Clay Materials. W. ARTHUR WHITE, Compilator. Pp. 55; tbls. 2. *Contains all published and unpublished analyses that are available for Illinois clay materials.*

Circ. 283. Economic Aspects of Direct Reduction of Iron Ore in Illinois. W. H. VOSKUIL and H. E. RISSER. Pp. 19; figs. 8; tbls. 4. *Direct reduction will supplement blast furnace reduction in areas where coking coal is not available or costly. This method can produce material that may be substituted for scrap iron as the charge for open hearth furnaces.*

Bull. 86. Upper Mississippian and Pennsylvanian Megaspores and Other Plant Microfossils from Illinois. MARCIA R. WINSLOW. Pp. 135; figs. 9; pls. 16; tbls. 3. *A preliminary investigation of land plant megaspores and other resistant plant parts occurring in coal and carbonaceous layers from Mississippian and Pennsylvanian sediments. The study indicated that megaspores may be useful for local correlation.*

Bull. 87. Petroleum Industry in Illinois, 1958. Pt. I. Oil and Gas Developments. Pt. II. Waterflood Operations. A. H. BELL, R. F. MAST, MARGARET O. OROS, and others. Pp. 117; pls. 2; figs. 5; tbls. 17. *Production increased 5 percent in 1958 over 1957 with 53 percent of production coming from secondary recovery by waterflooding.*

Indiana Geological Survey—Bloomington, 1959.

Rept. of Progress 14. Fossil Plants of Indiana. J. E. CANRIGHT. Pp. 45; pls. 5; tbls. 3; figs. 3. *Fossil plants comprising 146 species and belonging to 68 genera were found in southwestern Indiana.*

Rept. of Progress 15. Petrographic Similarity of Wisconsin Tills in Marion County, Indiana. W. HARRISON. Pp. 39; tbls. 4; figs. 5. *Compositional and textural similarities exhibited by the various till samples suggests uniformity of glacial processes and little variation in the source area for successive glaciations.*

Rept. of Progress 16. The Mt. Carmel Fault and Related Structural Features in South-Central Indiana. W. N. MELHORN and N. M. SMITH. Pp. 29; pl. 1; tbls. 2. *No evidence of graben structures or cross faulting as suggested by previous writers was noted in this study.*

Geological Survey of Japan—Hisamoto-chō, Kawasaki-shi, 1959.

Bulletin of the Geological Survey of Japan, Vol. 10, No. 8. Pp. 78. English abstracts. *Five papers concerning geochemistry, geophysics, ground water geology, and petrology.*

Bulletin of the Geological Survey of Japan, Vol. 10, No. 9. Pp. 102. English abstracts. *Nine papers concerning radiometric survey of various districts in Japan.*

Geologic Map of Ishinomaki. Scale, 1:200,000.

Kansas Geological Survey—Lawrence, 1959.

Bull. 134, Pt. 7. The Mineral Industry in Kansas in 1958. W. H. Schoewe. Pp. 243–287; tbls. 41; figs. 3. *Annual statistics for the mineral industry.*

Bull. 141. Ground-Water Levels in Observation Wells in Kansas, 1958. V. C. Fishel, E. L. Gulley, and E. L. Reavis. Pp. 146; figs. 24; tbls. 4. *Above-normal precipitation resulted in a rise of ground-water levels.*

New Zealand Geological Survey—Wellington, 1959.

Bull. 134. New Zealand Coals: Their Geological Setting and Its Influence on Their Properties. R. P. Suggate. Pp. 113; figs. 48; tbls. 6. Price, 12s.6d. *A discussion of Cretaceous and Tertiary coals with a range of rank from peat to semi-anthracite.*

Bull. n.s. 63. The Geology and Hydrology of Western Samoa. D. Kear and B. L. Wood. Pp. 92; figs. 40; tbls. 4; maps 5. Price, 40s. *Future development of the area depends to a large extent upon an adequate water supply which must be developed. Considerations concerning this development are explored.*

Sheet N85. Geological Map of New Zealand. Waiotapu. G. W. Grindley. *Map, scale 1:63,360.*

Sheet 21. Geological Map of New Zealand. Christchurch. L. E. Oborn and R. P. Suggate. *Map, scale 1:250,000.*

Ontario Department of Mines—Toronto, 1959.

Sixty-Seventh Annual Report, Vol. LXVII, Pt. 3, 1958. Geology of the Gripp Lake Area. F. F. Langford. Pp. 22; figs. 8. Map, scale 1 inch: 50 miles. *Sulfide minerals can be divided into two groups—disseminated chalcopyrite and pyrite associated with brecciation and shear zones in quartzite, and abundant pyrrhotite occurring in bands of iron formation.*

Sixty-Seventh Annual Report, Vol. LXVII, Pt. 4, 1958. Geology of the Wapesi Lake-Tully Lake Area. W. R. M. Williamson and P. P. Hudec. Pp. 11; photos 5; fig. 1. Geologic map, scale 1:63,360. *Geology of a typical Precambrian terrain; some iron formation; no economic deposits.*

Union of South Africa Geological Survey—Pretoria, 1958–59.

Bull. 27. The Chromite Deposits in the Rustenburg Area. G. P. Fourie. Pp. 45; pl. 1; tbls. 8; figs. 10; folders 6. Price, 7s. *The geology, petrology, and mineralography of chromitite seams of the Bushveld Igneous Complex.*

Bull. 28. Manganiferous Iron Ore, Hematite, Barite, and Sillimanite on Gams (Portion 1), Namaqualand. C. B. Coetzee. Pp. 30; pls. 4. Geologic map. Price, 4/6. *An epigenetic origin with subsequent thermal metamorphism is postulated for the iron and barite deposits of this area.*

Wyoming Geological Survey—Laramie, 1959.

Bull. 48. Structure and Petrology of the Northern Big Horn Mountains, Wyoming. F. W. Osterwald. Pp. 47; pls. 8; figs. 5; tbls. 2. *From available*

data it is inferred that the range was uplifted vertically, with little tilting, except at the margins.

Bull. 50. Mineral Resources of Wyoming. F. W. OSTERWALD, DORIS B. OSTERWALD, J. S. LONG, JR., and W. H. WILSON. Pp. 259; figs. 4. *A catalog of known mineral resources of Wyoming.*

U. S. Geological Survey—Washington, D. C., 1959.

Bull. 1028-L. Geology of Umnak and Bogoslof Islands, Aleutian Islands, Alaska. F. M. BYERS, JR. Pp. 267–369; pls. 13; figs. 6; tbls. 15. *Rocks of Umnak Island consist of late Tertiary and Quaternary volcanic rocks; those of Bogoslof Island are composed of historic lavas.*

Bull. 1028-M. Geology of Southern Adak Island and Kagalaska Island, Alaska. G. D. FRASER and G. L. SNYDER. Pp. 371–408; pls. 2; figs. 7; tbl. 1. *These islands are composed of an altered andesitic and basaltic sequence of marine pyroclastic deposits and lava flows.*

Bull. 1028-N. Some Effects of Recent Volcanic Ash Falls with Especial Reference to Alaska. R. E. WILCOX. Pp. 409–476; pls. 5; figs. 11. Price, 30 cents. *A mantle of ash more than a few inches thick can radically change runoff which in turn has important effects on water supply, agriculture, etc.*

Bull. 1069. Geology of the Thomas Range Fluorspar District, Juab County, Utah. M. H. STAATZ and F. W. OSTERWALD. Pp. 97; pls. 12; figs. 11; tbls. 8. *The fluorspar deposits are of three types—pipes, veins, and disseminated deposits; almost all deposits have an abnormally high uranium content.*

Bull. 1072-G. Coal Resources of Trinidad-Aguilar Area, Las Animas and Huerfano Counties, Colorado. R. L. HARBOUR and G. H. DIXON. Pp. 445–489; pls. 5; fig. 1. *Nearly 3 billion tons of bituminous coking coal are estimated to exist in beds of mineable thickness. No oil or gas has been discovered.*

Bull. 1079. Geology of the Charleston Phosphate Area, South Carolina. H. E. MALDE. Pp. 105; pls. 10; figs. 13; tbls. 5. Price, $1.75. *The phosphate rock is phosphatized copper marl reworked into the lower part of the Ladson formation, a Pleistocene marine deposit.*

Bull. 1082-C. Iron-Ore Resources of the United States Including Alaska and Puerto Rico, 1955. MARTHA S. CARR and C. E. DUTTON. Pp. 61–134; pl. 1; fig. 1; tbls. 6. Price, 75 cents. *The total domestic iron-ore resources are estimated at approximately 75,000 million long tons of crude ore.*

Bull. 1087-A. Geology of the Garo Uranium-Vanadium Copper Deposit, Park County, Colorado. V. R. WILMARTH. Pp. 21; pls. 5; figs. 2; tbls. 2. *Ore minerals are found in three faulted sandstone beds of the Maroon formation of Pennsylvanian and Permian age.*

Bull. 1087-C. Uranium Resources of the Green River and Henry Mountains Districts, Utah—A Regional Synthesis. H. S. JOHNSON, JR. Pp. 59–104; pls. 4; fig. 1. Price, $1.00. *About 78 percent of the reserves in the two districts are in the Morrison formation, and about 22 percent are in the Chinle formation.*

Bull. 1087-E. Stratigraphy and Uranium Content of the Chattanooga Shale in Northeastern Alabama, Northwestern Georgia, and Eastern Tennessee. LYNN GLOVER. Pp. 133–168; pls. 5; figs. 5; tbls. 2. Price, $1.00. *The average uranium content of 25 samples of shale selected in this region is about 0.005 percent. This average is above the regional average since sampling was limited to outcrops which gave relatively high scintillation-counter readings.*

Bull. 1097-A. Evaluation of the Lead-Alpha (Larsen) Method for Determining Ages of Igneous Rocks. DAVID GOTTFRIED, H. W. JAFFE, and F. E. SENFTLE. Pp. 63; pl. 1; figs. 6; tbls. 22. Price, 35 cents. *Lead-alpha ages of metamorphosed igneous rocks may approach the age of metamorphism instead of the age of the igneous activity. Discrepancies in measured ages of Precambrian zircon are still not satisfactorily explained.*

Bull. 1106-C. Geophysical Abstracts 178 July–September, 1959. D. B. VITALIANO, S. T. VESSELOWSKY, and others. Pp. 261–406. Price, 40 cents. *Abstracts of current literature pertaining to the physics of the solid earth and to geophysical exploration.*

Prof. Paper 313-A. The Phosphoria, Park City and Shedhorn Formations, in the Western Phosphate Field. V. E. MCKELVEY and others. Pp. 47; pls. 3; figs. 6; tbls. 7. Price, $1.00. *The paper proposes a new plan of nomenclature for these Permian rocks.*

Prof. Paper 316-C. Regional Geophysical Investigations of the Lisbon Valley Area, Utah and Colorado. P. E. BYERLY and H. R. JOESTING. Pp. 39–50; pls. 4; figs. 5. *The magnetic anomalies in the Lisbon Valley area, located in the east-central part of the Colorado Plateau, are caused mainly by variation in the magnetization of the basement rocks.*

Prof. Paper 354-A. Intrenched Meanders of the North Fork of the Shenandoah River, Virgina. J. T. HACK and R. S. YOUNG. Pp. 10; pl. 1; figs. 5; tbls. 2. Price, 20 cents. *A study of the channel of a river intrenched in hard rocks and an analysis of factors that cause it to meander.*

Economic Geology
Vol. 55, 1960, pp. 426–428

SCIENTIFIC NOTES AND NEWS

The Department of Geology of the University of Malaya has been transferred from Singapore to the Federation of Malaya. The new address is as follows: Department of Geology, University of Malaya, Pantai Valley, Kuala Lumpur, Malaya.

HAROLD E. THOMAS, Research Geologist, Ground Water Branch, Geological Survey has been assigned to Tunisia for two years under the auspices of the International Cooperation Administration. He will work there with ICA in its program to rebuild a ground-water organization which functioned at a high level of competence during the years of French colonial status. As a desert geologist "in search of green pastures," he will be working in an area where there are the ruins of a 60-mile aqueduct built during the reign of the Roman Emperor Hadrian.

The Ninth National Clay Conference, sponsored by the Clay Minerals Committee of the National Academy of Sciences—National Research Council, will be held at Purdue University, Lafayette, Indiana, on October 6, 7, and 8, 1960. A short field trip and laboratory visits are planned. All those interested in research or technology in fields related to clays or clay minerals are invited to participate. Two symposia are planned on "Engineering Aspects of Physico-Chemical Properties of Clays" and "Clay-Organic Complexes."

Stanford University received a gift from DELMER L. DAVES of his spectacular mineralogical collection which consists of more than 1,000 museum quality mineral specimens from all continents; 5,000 crystal, mineral and ore specimens for student use; more than 4,000 specimens of various rocks; a library of approximately 200 books on mineralogy, including several rare editions; and his own 50-volume index, illustrated in color and black and white.

"The Vetlesen Prize" has been established at Columbia University by the G. Unger Vetlesen Foundation for "outstanding achievement in the sciences resulting in a clearer understanding of the earth, its history or its relation to the universe." Like the Nobel Prizes, any person in any country may be nominated. The award, to be made every two years provided a worthy candidate is presented, consists of a gold medal, the sum of $25,000, and support of publication of the recipient's papers. The Foundation also announced that Dr. MAURICE EWING, geophysicist, oceanographer and director of Columbia University's Lamont Geological Observatory, has been selected as the first recipient of the Vetlesen Prize. Presentation was made at a dinner at Columbia on March 24. The principal speaker was Dr. ALAN T. WATERMAN, director of the National Science Foundation, Washington, D. C.

At the annual meeting of the AIMME, LOUIS and PAULINE MOYD, consulting geologists of Yonkers, N. Y., discussed and demonstrated operation of the "Berylometer," a portable detector that would "do for beryllium detection what the portable ultraviolet lamp has done for tungsten and Geiger and scintillation counters have done for uranium and thorium."

The 12th Berg- und Hüttenmännischer Tag will be held in Freiberg, Germany, June 8 to 11, 1960. Scientific sessions will be held on mining, metallurgy, geophysics, and oil. Field excursions are planned.

JOSEPH L. GILLSON, well-known chief geologist of the Du Pont Company's Development Department, retired on February 29. February also marked his inauguration as president of the American Institute of Mining, Metallurgical and Petroleum Engineers. Dr. Gillson joined du Pont in 1939 after spending three previous summers as a temporary employee. As chief geologist in the Development Department, he has made explorations in search of raw materials as well as investigations of ground water supplies, foundation problems and general site studies. ROBERT M. GROGAN has assumed Dr. Gillson's duties at du Pont, becoming manager of a newly formed Geology Division in the department.

BEN H. PARKER, vice-president and director of the Frontier Refining Company, Denver, will become the 44th president of The American Association of Petroleum Geologists on April 28. Serving with him on the Executive Committee will be LEWIS G. WEEKS, consulting geologist of Westport, Connecticut; FRANK B. CONSELMAN, consulting geologist, Abilene, Texas; GEORGE V. COHEE, U. S. Geological Survey, Washington, D. C.; and GROVER E. MURRAY, Boyd Professor of Geology at Louisiana State University, Baton Rouge.

WARREN JUDSON MEAD died in his home in Belmont, Mass., on January 16, 1960 at the age of 76. He was Emeritus Professor of Geology and Chairman of the Department of Geology of the Massachusetts Institute of Technology from 1934 until retirement in 1949. After retirement Professor Mead continued as Lecturer for five years giving lectures in Structural Geology and Engineering Geology.

BENO GUTENBERG, world authority on geophysics and seismology, and until his retirement two years ago, Director of the Seismological Laboratory of the California Institute of Technology, died in Pasadena, California on January 25 after a short illness. He was 70 years old.

JOHN B. PATTON has been appointed State Geologist of Indiana and Chairman of the Department of Geology at Indiana University. Dr. Patton has been serving in an acting capacity in both positions since the death of Dr. CHARLES F. DEISS in June, 1959.

RICHARD H. JAHNS of the Department of Geology of the California Institute of Technology has been appointed Chairman of the Division of Earth Sciences at Penn State, effective July, 1960, succeeding O. FRANK TUTTLE.

C. J STUBBLEFIELD has been appointed Director of the Geological Survey of Great Britain and Museum of Practical Geology, London, in succession to Sir WILLIAM PUGH, who retires on July 28. Dr. Stubblefield, who is 58, has been with the Geological Survey and Museum since 1928, as Paleontologist and latterly as Assistant Director.

BERNARD J. O'NEILL, JR. has left the New Jersey Zinc Company to join the Staff of Stanford Research Institute as a geologist.

The American Association of Petroleum Geologists has announced the following recipients of honorary membership: LEONIDAS T. BARROW, Houston, Texas; CHARLES J. HARES, Boulder, Colorado; ROY T. HAZZARD, Rocksprings, Texas; SAMUEL H. KNIGHT, Univ. of Wyoming; ROBERT B. MORAN, Pasadena, California; and EDGAR W. OWEN, San Antonio, Texas.

HENRY V. HOWE of the School of Geology, Louisiana State University, has been chosen to receive the Sidney Powers Memorial Medal of the A.A.P.G.—the

highest honor in petroleum geology. Dr. Howe is the 13th recipient of this award which is made in recognition of distinguished and outstanding contributions to or achievements in petroleum geology.

Shell Companies Foundation, Inc. announces that it will contribute $1,430,000 in 1960 for educational, charitable, religious, and public service organizations. The amount, one of the largest in industry and a new high for the Foundation, is made possible by substantial gifts which the Foundation has received from Shell Oil Company and its subsidiaries. This marks the sixth successive year that the Foundation budget has exceeded a million dollars. Aid-to-education programs receive the largest share of the budget—approximately $900,000, an increase of more than $200,000 over 1959.

ADVERTISEMENTS

Patrons of this journal are requested to refer to ECONOMIC GEOLOGY AND THE BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS when consulting advertisers.

ROCK ANALYSIS FOR GEOLOGICAL RESEARCH

Rapid accurate results from an authoritative laboratory—carefully directed by graduate chemists and physicists—using modern techniques—spectrographic—spectrophotometric—chemical—reporting results six weeks after receipt of samples or sooner.

Request Details or Submit Samples to:

TECHNICAL SERVICE LABORATORIES

355 KING STREET WEST TELEPHONE EMpire 2-4248
TORONTO 2B CANADA

Specialists in rock and mining analysis

Research facilities available for:

Ore Dressing—process development—extractive metallurgy investigations—mill and plant analytical control methods

FIFTIETH ANNIVERSARY VOLUME

ECONOMIC GEOLOGY

1905–1955

CONTENTS

Part I

FOREWORD ii
ECONOMIC GEOLOGY ..... *Alan M. Bateman* 1
METALLOGENETIC PROVINCES AND EPOCHS ..... *F. S. Turneaure* 38
THERMAL SPRINGS AND EPITHERMAL ORE DEPOSITS ..... *Donald E. White* 99
THE CLASSIFICATION OF ORE DEPOSITS ..... *James A. Noble* 155
STRUCTURE OF HYDROTHERMAL ORE DEPOSITS ..... *H. E. McKinstry* 170
THE ZONAL THEORY OF ORE DEPOSITS ..... *Charles F. Park, Jr.* 226
TEMPERATURES IN AND NEAR INTRUSIONS ..... *T. S. Lovering* 249
SYNTHETIC MINERALS ..... *W. A. Weyl* 282
HYDROTHERMAL ALTERATION AS A GUIDE TO ORE ..... *George M. Schwartz* 300
OXIDATION OF COPPER SULFIDES AND SECONDARY SULFIDE ENRICHMENT *Charles A. Anderson* 324
METHODS AND PROBLEMS OF GEOLOGIC THERMOMETRY ..... *Earl Ingerson* 341
SEDIMENTARY DEPOSITS OF RARE METALS ..... *Konrad B. Krauskopf* 411
ORIGIN OF URANIUM DEPOSITS ..... *V. E. McKelvey, D. L. Everhart and R. M. Garrels* 464

Part II

ENGINEERING GEOLOGY—A FIFTY YEAR REVIEW ..... *Robert F. Legget* 534
INFLUENCE OF GEOLOGICAL FACTORS ON THE ENGINEERING PROPERTIES OF SEDIMENTS ..... *Karl Terzaghi* 557
RECENT DEVELOPMENTS IN CLAY MINERALOGY AND TECHNOLOGY *Ralph E. Grim* 619
PROPERTIES OF CALCIUM AND MAGNESIUM CARBONATES AND THEIR BEARING ON SOME USES OF CARBONATE ROCKS ..... *D. L. Graf and J. E. Lamar* 639
THE QUANTITATIVE APPROACH TO GROUND-WATER INVESTIGATIONS *John G. Ferris and A. Nelson Sayre* 714
TIME OF PETROLEUM ACCUMULATION ..... *A. I. Levorsen* 748
COAL PETROLOGY ..... *C. E. Marshall* 757
THE USE OF GAMMA RAY MEASUREMENTS IN PROSPECTING *William L. Russell* 835
ECONOMIC APPLICATIONS OF PALEOCOLOGY ..... *Samuel P. Ellison* 867
GEOPHYSICS APPLIED TO PROSPECTING FOR ORES ..... *Louis B. Slichter* 885
MINOR ELEMENTS IN SOME SULFIDE MINERALS ..... *Michael Fleischer* 970
THE STUDY OF PEGMATITE DEPOSITS ..... *Richard H. Jahns* 1025–1130

order from

ECONOMIC GEOLOGY PUBLISHING COMPANY

105 Natural Resources Building, Urbana, Illinois

Price to Subscribers (including members, non-member Journal subscribers, and students whether subscribers or not) $6.00

Price to Non-Subscribers to Journal 8.00

IMPORTANT McGRAW-HILL BOOKS

GEOLOGY: Principles and Processes, *New Fifth Edition*

By WILLIAM H. EMMONS, IRA S. ALLISON, *Oregon State College;* GEORGE A. THIEL, *University of Minnesota;* and CLINTON R. STAUFFER, *California Institute of Technology.* Ready in April.

A textbook for a beginning one-semester course in Physical Geology. It has been a standard and leading text for this field for over 27 years. This new fifth edition has been the most extensive of all its revisions. It is receiving special editing treatment and the result will be a completely rewritten text, with entirely new art work done by a professional scientific illustrator, and a skilled use of two colors throughout. The text is suitable for both terminal cultural courses, or for introductory courses for majors in the subject.

INTRODUCTION TO GEOPHYSICAL PROSPECTING, *New Second Edition*

By MILTON B. DOBRIN, *Triad Oil Company, Ltd., Calgary, Alberta, Canada.* 446 pages, $9.50

A thorough revision of a highly successful text. It is designed to present the principles of current techniques of geophysical prospecting for oil and minerals to students and technical personnel employed in the fields of petroleum and mineral exploration. The book covers all the major methods of geophysical prospecting. For each method it discusses fundamental physical principles, instruments, field techniques, reduction of data, interpretation, and examples showing results of actual surveys.

Petroleum Reservoir Engineering: Physical Properties

By JAMES W. AMYX, DANIEL M. BASS, JR., and ROBERT L. WHITING, *all of the Agricultural and Mechanical College of Texas.* Ready in April.

This is the first volume of a two-volume work on Reservoir Engineering. This volume develops the fundamental concepts of rock and fluid properties on which reservoir engineering is based. Procedures are presented for reduction and organization of reservoir rock, fluid and production measurements for use in reservoir engineering studies. Emphasis is on up-to-date problems of Reservoir Engineering.

Principles of Petroleum Geology *New Second Edition*

By WILLIAM L. RUSSELL, *Agricultural and Mechanical College of Texas.* Ready in April.

An up-to-date, carefully revised edition of one of the most important books in this academic area. The book gives students and geologists a description of the principles and processes that are important in petroleum geology. New information on the origin and accumulation of petroleum is discussed at length. The concept of traps for oil and gas is described and illustrated. A brief discussion of well logging methods and of geophysics is given.

Send for copies on approval

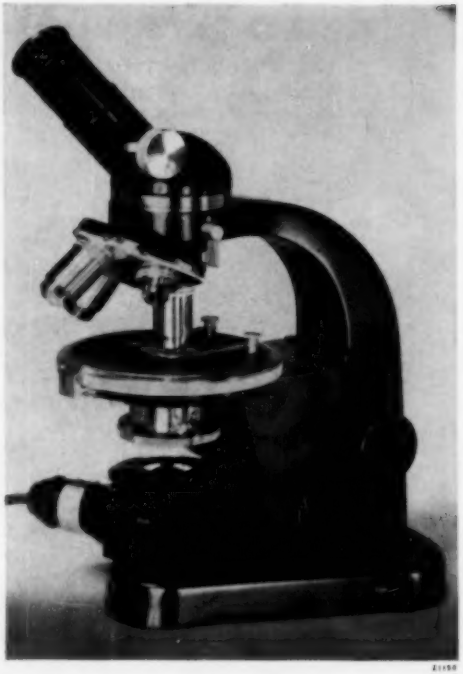
McGRAW-HILL BOOK COMPANY, INC.

330 West 42nd Street **New York 36, N.Y.**

Leitz **first in precision optics**

NEW POLARIZING MICROSCOPE SM-pol

Leitz sets a new standard with this student polarizing and chemical microscope of modern design, with dual, low-position focusing controls and large field of view. A reasonably priced polarizing microscope, the model SM-pol, has rugged, one-piece construction with Bertrand lens and pinhole diaphragm built into the tube. Inclined monocular tube will accommodate wide-field eyepieces and the microscope can be used faced away from the observer, permitting easy accessibility to the stage.



A reputation for integrity and a tradition of service have led thousands of scientific workers to bring their optical problems to Leitz. If you have problems in this field, why not let us help you with them?

See your Leitz dealer and examine these Leitz instruments soon. Write for information.

E. LEITZ, INC., Dept. G-3
468 Fourth Avenue, New York 16, N. Y.

Please send me the Leitz _____ brochure.

NAME _____

STREET _____

CITY _____ ZONE _____ STATE _____

E. LEITZ, INC., 468 FOURTH AVENUE, NEW YORK 16, N. Y.
Distributors of the world-famous products of Ernst Leitz G. m. b. H., Wetzlar, Germany—Ernst Leitz Canada Ltd.
LEICA CAMERAS · LENSES · MICROSCOPES · BINOCULARS

Fastest Method of Making Polished Ore Sections

The Improved SAMPSON-PATMORE
ROCK POLISHING MACHINE

- Speed electrically varied, at a touch of the dial, from 100 to 1,000 r.p.m.
- Silent operation

Made by the makers of the
ISODYNAMIC
Magnetic Separator

Diamond-abrasive polishing preceded by fine grinding! With this method, the average ore specimen may be fine ground and polished by taking approximately one minute on each of five laps plus a minute between stages for examining the work.

For fine grinding, two 11-in. laps are used with different grades of aluminum oxide abrasives at speeds of 125–150 r.p.m. For polishing, three 8-in. laps, covered with silk bolting cloth, are used with diamond abrasives at speeds from 350 to 800 r.p.m. or more depending on the material being polished. The laps, fitting a single spindle, are interchanged in a matter of seconds as grinding and polishing progress.

For description of Professor Sampson's method, see Economic Geology, Vol. 51, No. 5, August, 1956. *Write for Bulletin*

S. G. FRANTZ Co., Inc.
E N G I N E E R S

322 Kline Ave. at Brunswick Pike...P. O. Box 1138...Trenton 6, N. J. U. S. A.
Cable Address: MAGSEP, Trentonnewjersey

INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

BULLETIN GÉODÉSIQUE

BEING

THE JOURNAL OF

THE INTERNATIONAL ASSOCIATION of GEODESY

★ ★ ★

The scientific articles appearing in this quarterly journal are prepared by the foremost geodesists and geophysicists in the world and deal with the following subjects: Mathematical geodesy (instruments, observations, calculation and adjustment of triangulation); astronomical determination of geographic positions; dynamic geodesy (gravimetry, figure of the Earth, earth tides, isostasy, etc.); leveling. It also contains a section of book notices.

Quarterly *1 volume per year $6.00 (£2.0.0) per volume*

Published by

PERGAMON PRESS

NEW YORK LONDON PARIS LOS ANGELES

122 East 55th Street, New York 22, N.Y. 4 & 5, Fitzroy Square, London W.1.

d. m. organist

PETROGRAPHIC LABORATORY

BOX 176 • NEWARK, DELAWARE

THIN SECTIONS OF

ROCKS, MINERALS, ORES, CERAMICS

PREPARED ROCK SECTIONS FOR STUDENT USE

GRAIN COUNTS • PETROGRAPHIC ANALYSIS

PETER C. BADGLEY

STRUCTURAL METHODS FOR THE EXPLORATION GEOLOGIST

This one volume covers almost every currently used structural method, and brings together tables, nomographs, and maps previously found only in many scattered publications. 8⅝" × 11", 281 pp. $7.50.

ROBERT L. BATES

GEOLOGY OF THE INDUSTRIAL ROCKS AND MINERALS

The first geologic-genetic treatment of the nonmetallics, describing thirteen rocks and twenty minerals, mainly in United States deposits. Also discusses extraction, preparation, use, and mineral economics. New genetic classification featured. 424 pp. $10.00.

WILLIAM H. EASTON

INVERTEBRATE PALEONTOLOGY

A functional approach presenting animals in customary systematic order, discussing their biology for the reader with little or no biological training. Gives only that morphological detail necessary for identifications. 701 pp. $10.00.

ROBERT M. GARRELS

MINERAL EQUILIBRIA: AT LOW TEMPERATURE AND PRESSURE

A detailed discussion of geologic aspects of low temperature aqueous chemistry, describing, for even the reader with little chemical background, ways of representing mineral relations, with special reference to partial pressure and pH-potential diagrams. 254 pp. $6.00.

W. W. MOORHOUSE

THE STUDY OF ROCKS IN THIN SECTION

This systematic petrography manual combines in one volume a summary of the methods of optical mineralogy; descriptions of the common rock-forming minerals; determinative tables; and descriptions of the common igneous, sedimentary, and metamorphic rocks and ores. 514 pp. $8.00.

F. ALTON WADE & RICHARD B. MATTOX

ELEMENTS OF CRYSTALLOGRAPHY AND MINERALOGY

A logical, step-by-step introduction to the theories and principles of crystallography and mineralogy in well-illustrated, detailed discussions that cover the subject matter comprehensively. 316 pp. $7.50.

J. MARVIN WELLER

STRATIGRAPHIC PRINCIPLES AND PRACTICE

This introduction to stratigraphy discusses those features of sedimentology, paleontology, and tectonics that find particular application in stratigraphy, basing the interpretation of sedimentary rocks on information from these fields. 679 pp. $10.00.

HARPER & BROTHERS, 49 East 33d Street, New York 16

ADDED TO HARPER'S GEOSCIENCE SERIES

Special Price—

A.A.P.G. COMPREHENSIVE INDEXES, 1917—1955

Encompass all A.A.P.G.'s Bulletins and special publications for a 38-year period.
A valuable addition to the geologist's library. Cloth bound.

BOTH INDEXES	member price, $5.00; others, $7.00		
SINGLY	1917–45, one volume	3.00	4.00
	1946–55, one volume	3.00	4.00

ORDER FROM

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
Box 979, Tulsa 1, Oklahoma, U. S. A.

THIN SECTIONS
Processed to your specifications from Rocks, Minerals Well Cuttings

Mounted Polished Ore Sections

Charge Schedule sent upon request.

Established 1949

Fred Roberts » » »

PETROGRAPHIC SECTION SERVICE

1300 S. MONTEREY PASS RD., MONTEREY PARK, CALIF.

SWAN ENGRAVING COMPANY

PHOTO ENGRAVERS COMMERCIAL ARTISTS

BRIDGEPORT, CONN. NEW HAVEN, CONN

POUGHKEEPSIE, N.Y.

Geophysics for Economic Geologists

GEOPHYSICAL CASE HISTORIES, VOLUME I (1948)	$10.00
GEOPHYSICAL CASE HISTORIES, VOLUME II (1956)	$10.00
CUMULATIVE INDEX, 1931–1953 (All publications)	$5.00
GEOPHYSICS Per year	$10.00

Detailed list of publications on request

Send Order with Remittance to

SOCIETY OF EXPLORATION GEOPHYSICISTS
Box 1536 Tulsa 1, Oklahoma

PROBLEMS OF PETROLEUM GEOLOGY

Sidney Powers Memorial Volume

A Sequel to *Structure of Typical American Oil Fields*

A compilation of 43 papers prepared for this volume by 47 authors

1,073 pp., 200 illus. Cloth. Price, postpaid: to members, $4.00; to non-members, $5.00. Usual discounts to educational institutions.

The American Association of Petroleum Geologists
Box 979 . . . Tulsa 1, Oklahoma

A COMPLETE PRINTING SERVICE

GOOD PRINTING does not just happen; it is the result of careful planning. The knowledge of our craftsmen, who for many years have been handling details of composition, proofreading, presswork and binding, is at your disposal. For seventy-five years we have been printers of scientific and technical journals, books, theses, dissertations and works in foreign languages. Consult us about your next printing job.

• PRINTERS OF • ECONOMIC GEOLOGY

LANCASTER PRESS, Inc.

PRINTERS • BINDERS • ELECTROTYPERS

ESTABLISHED 1877 LANCASTER, PA.

Announcing

SPECIAL STUDENT SUBSCRIPTION RATES

ECONOMIC GEOLOGY

and the Bulletin of the Society of Economic Geologists:

An international journal devoted to the field of Economic Geology

Edited by ALAN M. BATEMAN

Business Editor, MORRIS M. LEIGHTON

8 issues per year

Regular subscription rate, $6.50, student rate, $4.00

(Canadian postage, 30¢)

Students registered in geology courses in the United States and Canada may send for application blank to: **Economic Geology Publishing Company, 105 Natural Resources Building, Urbana, Illinois.**

Wiley BOOKS

OPTICAL CRYSTALLOGRAPHY, Third Edition

With Particular Reference to the Use and Theory of the Polarizing Microscope

By ERNEST E. WAHLSTROM, *University of Colorado.* Deals with the theory and practice of optical crystallography, with special emphasis placed on the use of the polarizing microscope in the study of crystals and fragments in visible transmitted light. *1960. Approx. 352 pages. Prob. $8.50.*

MICROSCOPIC SEDIMENTARY PETROGRAPHY

By ALBERT V. CAROZZI, *University of Illinois.* Provides complete microscopic descriptions of the most frequently found sedimentary rock-types. *1960. Approx. 464 pages. $11.50.*

SUBSURFACE MAPPING

By MARGARET S. BISHOP, *University of Houston.* Discusses the various kinds of maps that may be constructed to present subsurface data, and explains the ways in which these maps are interpreted. *1960. 198 pages. $5.75.*

THE SEA OFF SOUTHERN CALIFORNIA

A Modern Habitat of Petroleum

By K. O. EMERY, *University of Southern California.* Integrates basic knowledge available about marine geology, and summarizes very pertinent data on underwater oil resources. *1960. 366 pages. $12.50.*

PETROLEUM GEOLOGY, Second Edition

By KENNETH K. LANDES, *University of Michigan.* Synthesizes the modern theories about the geological occurrence of oil in the earth's crust and how commercial deposits of that oil can be found by man. *1959. 443 pages. $9.50.*

HISTORICAL GEOLOGY, Second Edition

By CARL O. DUNBAR, *Yale University.* Includes new advances in geochronology, the cosmic history of the earth, and the new discoveries in vertebrate paleontology and in human paleontology. *1960. 477 pages. $7.95.*

LITHOFACIES MAPS

An Atlas of the United States & Southern Canada

By L. L. SLOSS, E. C. DAPPLES, *and* W. C. KRUMBEIN, *all of Northwestern University.* Contains about 150 rock- and time-stratigraphic units. *1960. In Press.*

CRYSTAL-STRUCTURE ANALYSIS

By MARTIN J. BUERGER, *M.I.T.* Concerned with the whole field of crystal-structure analysis. Covers all phases of the gathering of data, and the ways of treating the material to find the arrangements of atoms. *1960. Approx. 664 pages. Prob. $16.00.*

Send for examination copies.

JOHN WILEY & SONS, Inc.

440 Park Avenue South, N.Y. 16, N.Y.